MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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315 G - 3

A MECHANICAL DUPLEXER FOR HIGH-POWERED X-BAND RADARS

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LEXINGTON MASSACHUSETTS

A MECHANICAL DUPLEXER FOR HIGH-POWERED X-BAND RADARS

The combination of high power and the use of a low-noise maser receiving system places severe requirements on modern radar duplexing systems. Typical values of isolation of -120 db and insertion loss of less than -0.2 db are required to prevent deterioration of the maser gain and low-noise capabilities. The only presently available system that can approach the needed performance is the mechanical duplexer. The unit discussed below was developed for the West Ford radar system. The requirements of this unit are presented in Table 1.

The advantages of a mechanical duplexer are:

1. The system is broad band - no tuning is needed.
2. The isolation can be very high (> 100 db).
3. The insertion loss is very low (< 0.2 db).

The disadvantages are:

1. The system is not flexible, i.e., the duty cycle and repetition rate are fixed.
2. The switching time is not fast. The minimum switching time being about 0.5 ms. (ms = millisecond.)
3. The system is a mechanical one with the attendant ills of vibration, bearing wear and maintenance.

Figure 1 shows the schematic form of the mechanical duplexer. This arrangement is a balanced duplexer, used commonly with the switching element being either a gas tube or a ferrite switch. A discussion of the hybrid action is given in the appendix. In the mechanical duplexer, the rotating blade provides the necessary switchable short circuit across the waveguide. Figure 2 shows the geometry of the system and the relevant parameters. Figure 3 shows the timing sequence for the West Ford system. Figures 4 and 5 show the re-

lationship of the duplexer parameters. The value of 0.75 ms was chosen for the switching time. This gave values of $\psi = 27^{o}$ and R = 7.6". T_1 was fixed at 3 ms. One blade gives f = 20 cps = 1200 rpm. The duplexer unit was constructed on the basis of these parameters. A synchro generator is included to allow dynamic data presentation. A light source, photo diode and slotted disc are used to provide a pulse to keep the duplexer in synchronism with the transmitter-timing sequence. The duplexer shaft is driven by a synchronous motor. The motor is excited by a 20 cps power oscillator which is kept in "sync" with the transmitter pulse. The completed unit is shown in Figures 6, 7 and 8. The original unit had a blade thickness of 0.090" and a blade-to-choke gap of 0.030". Two separate blades and choke sections were used to provide some design margin in meeting the 120 db isolation specifications. The measurement techniques used in testing the duplexer will be described in a later section.

The first measurements of the duplexer showed a high input VSWR, large insertion loss and poor isolation. Subsequent tests proved that the choke design was at fault. The original choke design is shown in Figure 9. A great deal of data was next taken on various choke configurations with blade and gap separations as variables. The final design selected as being superior to all others tested was that of the commercial dual-waveguide choke. This configuration is shown in Figure 10. The data on this choke also showed that, with a blade thickness of 0.040" and a gap from choke-to-blade of 0.015", an insertion loss of about 0.1 db from the antenna to the maser would be feasible. See Figures 11 and 12.

A modified unit was built and the test results are shown below.

Table 2 shows that the low-level insertion loss is now acceptable. The

input VSWR is about 1.15:1.0 at any terminal except during the switching time and the maximum is about 1.22:1.0 (Figure 13). This is considered acceptable. The -120 db loss from transmitter to maser is not achieved. Figures 14a, b, c, d, e and f show the loss from various combinations of ports. The maximum loss is seen to be about -95 db. Since leakage could occur either around the cavity formed by the circular castings or directly across the blade, a series of tests was made to determine the leakage path. An RF absorber in sheet form, 5/32" thick, was cemented in voids previously allowed in the castings for just this purpose (Figure 15). The isolation measurements were repeated and no measurable change resulted from the addition of the absorber. It was assumed that the leakage was predominately around the blade.

A new series of chokes was placed outside the present chokes. These can be seen in Figure 16. The choke was placed only on the center casting since this was easier to modify than the outside units. Figures 17a, b, c and d show that the isolation has been now reduced to about -105 db but the width of the isolation curve is only about 1 ms. Two modifications were next tried. An X-band absorber material (Emerson Cummings Company MF-124 bulk absorber) was placed around the choke area of the outside castings (See Figure 18), and the blade sector angle was increased from 27° to 36°. The insertion loss and isolation data was repeated and the results are shown in Figures 19a, b, c and d. The low-level loss is still good, being less than 0.1 db. The high-level loss is greater than -120 db and the width of the isolation curve at -120 db is now 2.23 ms. The end and start of the receive time occupy 5.29 ms. This gives a switching time of about 1.5 ms. Since the duplexer was urgently needed in the West Ford system, an isolation test was performed at the West Ford site at

Millstone Hill using the more sensitive exciter - mixer preamp assembly. The data is the same as that taken before. The lowest readable level was about -125 db. Leakage of energy from the exciter rack prevented greater sensitivity from being achieved.

The present microwave design of the duplexer is considered satisfactory. However, if time permitted, a number of modifications could be incorporated in the duplexer. These are listed below:

1. Dual chokes installed on all choke sections.
2. Absorber placed around all the choke assemblies.
3. The center casting made $3/4\ \lambda g$ instead of approximately $1/2\ \lambda g$.
4. A compromise blade angle between 27° and 36°.

MEASUREMENT TECHNIQUES FOR MECHANICAL DUPLEXER

It was required to measure VSWR, insertion loss and isolation of the duplexer as a function of rotation for several frequencies. A dynamic presentation of the data was necessary, and the system discussed below proved completely satisfactory.

The basic measuring device is an antenna-pattern recorder with the angle axis driven by a synchro generator attached to the duplexer shaft and the signal axis driven by either signals proportional to VSWR or insertion loss. The equipment set-up is shown in Figures 20a and b. The low-level insertion loss was measured by conventional means using a VSWR meter as an indicator. The VSWR was measured using a modified reflectometer system. Auxiliary tuners TX and TY (Figure 20a) enable one to tune this system at one frequency so that the generator mismatch and finite directivity of the coupler do not limit the accuracy of the system*. Return losses of 50 db were easily measured. This corresponds to a VSWR of less than 1.01:1.0. Calibration is achieved by placing a short circuit at the output end of the coupler and then setting 0 db in the variable attenuator on the auxiliary arm of the coupler. This gives a reflection coefficient of 1.00 or VSWR of ∞. By placing various values of attenuation in the auxiliary line, the recorder paper may be calibrated in VSWR or reflection coefficient. Once the calibration is complete, the duplexer is inserted in the system and rotated by hand. A plot of VSWR vs. rotation is thereby automatically obtained.

* G. F. Engen and R. W. Beatty, "Microwave Reflectometer Techniques," IRE Trans. on Microwave Theory and Techniques, Vol. MTT-7, pp. 351-355; July 1959.

The high isolation data was taken using a + 30 dbm source and, with the -85 dbm sensitivity of the pattern recorder, a minimum detectable signal of about -115 db was achieved. Fixed waveguide pads were used to provide calibration points. The loss data was taken in two ranges because the recorder paper has only a 60 db dynamic range. It was felt that to take readings greater than -115 db, it would be necessary to use the receiving equipment at the Millstone-West Ford Site. However, for the preliminary testing, the present pattern recorder sensitivity was adequate.

APPENDIX

Hybrid Properties

The scattering matrix of a 3 db hybrid is given by*

$$S = \frac{1}{\sqrt{2}} \left|\begin{array}{cc|cc} 0 & 0 & 1 & j \\ 0 & 0 & j & 1 \\ 1 & j & 0 & 0 \\ j & 1 & 0 & 0 \end{array}\right|$$

where the ports are as shown in Figure A-1, the hybrid is assumed matched and with perfect decoupling.

Let $P_1 = 1$ or $\frac{1}{2} a_1 a_1^* = 1$. a^* is the complex conjugate of a. Writing out the elements of S we have

$$\begin{cases} b_3 = \dfrac{a_1}{\sqrt{2}} \\ b_4 = \dfrac{j a_1}{\sqrt{2}} \end{cases}$$

then $P_3 = \frac{1}{2} b_3 b_3^* = \frac{1}{2}\left(\frac{a_1}{\sqrt{2}}\right)\left(\frac{a_1^*}{\sqrt{2}}\right) = \frac{1}{2}$

$P_4 = \frac{1}{2} b_4 b_4^* = \frac{1}{2}$

this is, of course, the usual hybrid property of equal power split. If we now place a short at plane S-S, Figure A-1, we can write $a_3 + b_3 = a_4 + b_4 = 0$.

We now have a two-terminal system and we can write after reductions

$$\begin{cases} b_1 = -ja_2 \\ b_2 = -ja_1 \end{cases}$$

Now for $P_1 = \frac{1}{2} a_1 a_1^* = \frac{1}{2} (jb_2)(jb_2)^* = \frac{1}{2} b_2 b_2^*$.

* Radiation Laboratory series #8, "Principles of Microwave Circuits," pp. 448.

Then all the power is delivered to port 2. If port 2 is matched then $a_2 = 0$ and also $b_1 = 0$, or port 1 is also matched.

Consider now the tandem arrangement of hybrids as shown in Figure A-2. The scattering matrix of the cascade can be computed from another matrix called the transfer matrix. This is defined as:

$$\begin{bmatrix} b_2 \\ a_2 \\ b_1 \\ a_1 \end{bmatrix} = \begin{bmatrix} T \end{bmatrix} \begin{bmatrix} a_4 \\ b_4 \\ a_3 \\ b_3 \end{bmatrix} \quad \text{or } T' = \frac{1}{2} \left[\begin{array}{cc|cc} 1 & 0 & j & 0 \\ 0 & 1 & 0 & -j \\ \hline j & 0 & 1 & 0 \\ 0 & -j & 0 & 1 \end{array} \right]$$

Now $T = T' \; T''$

and we have $T = \left[\begin{array}{cc|cc} 0 & 0 & j & 0 \\ 0 & 0 & 0 & -j \\ \hline j & 0 & 0 & 0 \\ 0 & -j & 0 & 0 \end{array} \right]$

Changing from the T matrix to the S matrix, we have for the cascade

$$S = \left[\begin{array}{cc|cc} 0 & 0 & 0 & j \\ 0 & 0 & j & 0 \\ \hline 0 & j & 0 & 0 \\ j & 0 & 0 & 0 \end{array} \right]$$

this means $S_{14} = S_{41} = j$ and $S_{23} = S_{32} = j$. All other $S_{jk's} = 0$. Therefore, the signal at port 1' goes to port 4'' and from port 2' to port 3'' and all other combinations are decoupled.

CAPTIONS

Figure 1: Schematic of Mechanical Duplexer

Figure 2: Geometry of Mechanical Duplexer

Figure 3: West Ford Timing Sequence

Figure 4: Switching Time vs. Blade Angle

Figure 5: Switching Time vs. Radius of Blade and Waveguide Angle

Figure 6: Mechanical Duplexer (Complete Unit)

Figure 7: Mechanical Duplexer (Outer Housing)

Figure 8: Mechanical Duplexer (Blade Assembly)

Figure 9: Original Choke Design

Figure 10: New Choke Design

Figure 11: Insertion Loss and VSWR vs. Choke-to-Short Spacing

Figure 12: Insertion Loss and VSWR vs. Choke-to-Choke Spacing

Figure 13: VSWR vs. Rotation of Mechanical Duplexer

Figure 14(a): Insertion Loss vs. Rotation, of ports 1 to 4 (0-60db)
(b): Insertion Loss vs. Rotation, of ports 1 to 4 (60-120db)
(c): Insertion Loss vs. Rotation, of ports 1 to 2 (0-60db)
(d): Insertion Loss vs. Rotation, of ports 1 to 3 (0-60db)
(e): Insertion Loss vs. Rotation, of ports 1 to 3 (60-120db)
(f): Insertion Loss vs. Rotation, of ports 2 to 4 (60-120db)

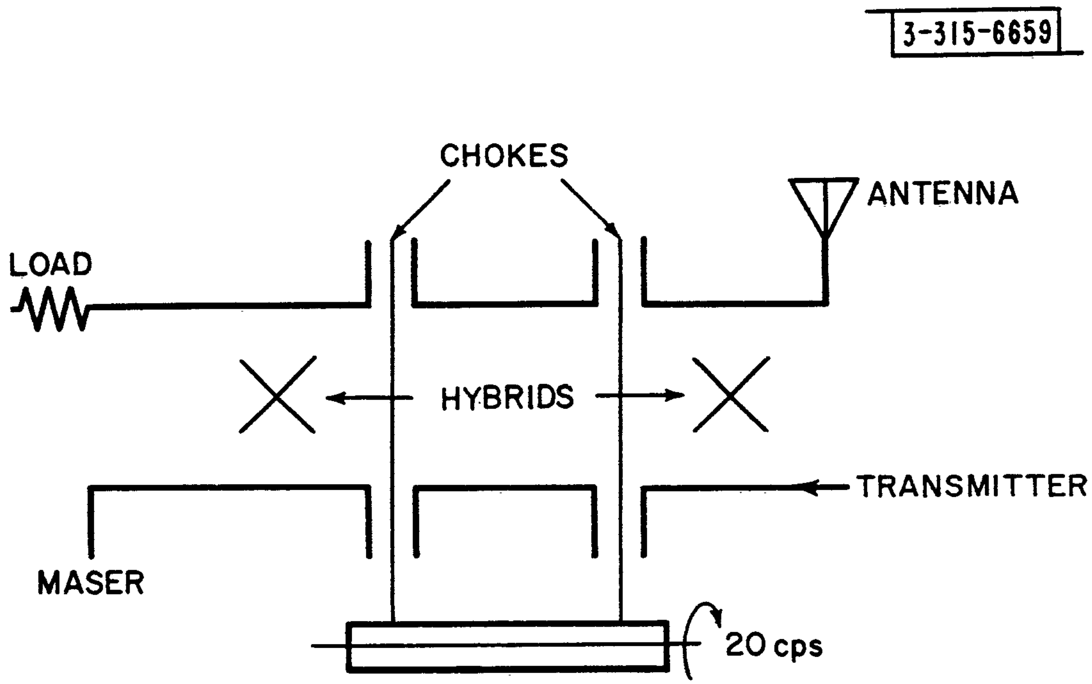
Figure 15: Mechanical Duplexer with Absorber in Place

Figure 16: Mechanical Duplexer with New Chokes Added

Figure 17(a): Insertion Loss vs. Rotation, of ports 1 to 4 (0-60db)
(b): Insertion Loss vs. Rotation, of ports 1 to 4, 1 to 3 (60-120db)
(c): Insertion Loss vs. Rotation, of ports 1 to 3 (0-60db)
(d): Insertion Loss vs. Rotation, of ports 1 to 2 (0-60db)

Figure 18: Mechanical Duplexer with Absorber Added to Choke Region

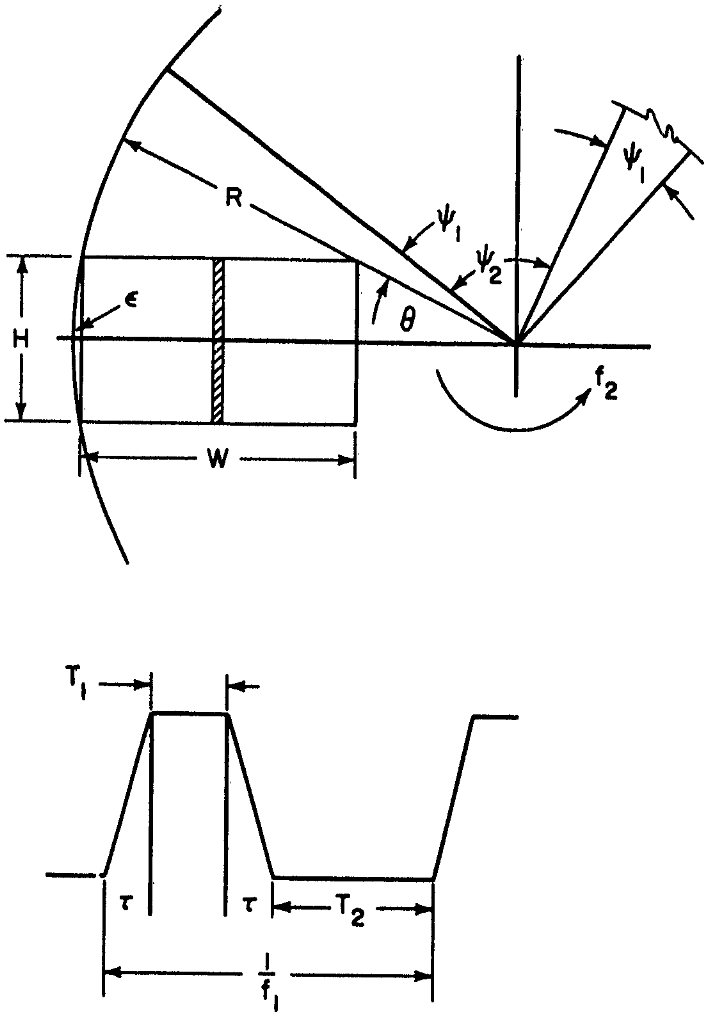
TABLES



3-315-6659
CHOKES
ANTENNA
LOAD
HYBRIDS
TRANSMITTER
MASER
20 cps

Figure 1

3-315-6660



$R = W + H/2 \cot\theta + \epsilon$
FOR $R \geq 5H, \epsilon \doteq 0.01R$
$R \doteq W + H/2 \cot\theta$

SYMBOLS:

τ = SWITCHING TIME
T_1 = ON TIME
T_2 = OFF TIME
f_1 = REPETITION RATE
f_2 = BLADE ROTATION SPEED
n = NUMBER OF BLADES

RELATIONS:

$$R = W + H/2 \cot\theta \qquad (1)$$

$$f_1 = n f_2 \qquad (2)$$

$$1/f_1 = 2\tau + T_1 + T_2 \qquad (3)$$

$$\tau = \frac{2\theta}{2\pi f_2} \qquad (4)$$

$$T_1 = \frac{\psi_1 - 2\theta}{2\pi f_2}, \quad T_2 = \frac{\psi_2 - 2\theta}{2\pi f_2} \qquad (5a, b)$$

$$\psi_1 + \psi_2 = 2\pi/n \qquad (6)$$

$$\psi_1, \psi_2 \geq 2\theta \text{ OR } n \leq \frac{\pi}{2\theta} \qquad (7)$$

Figure 2

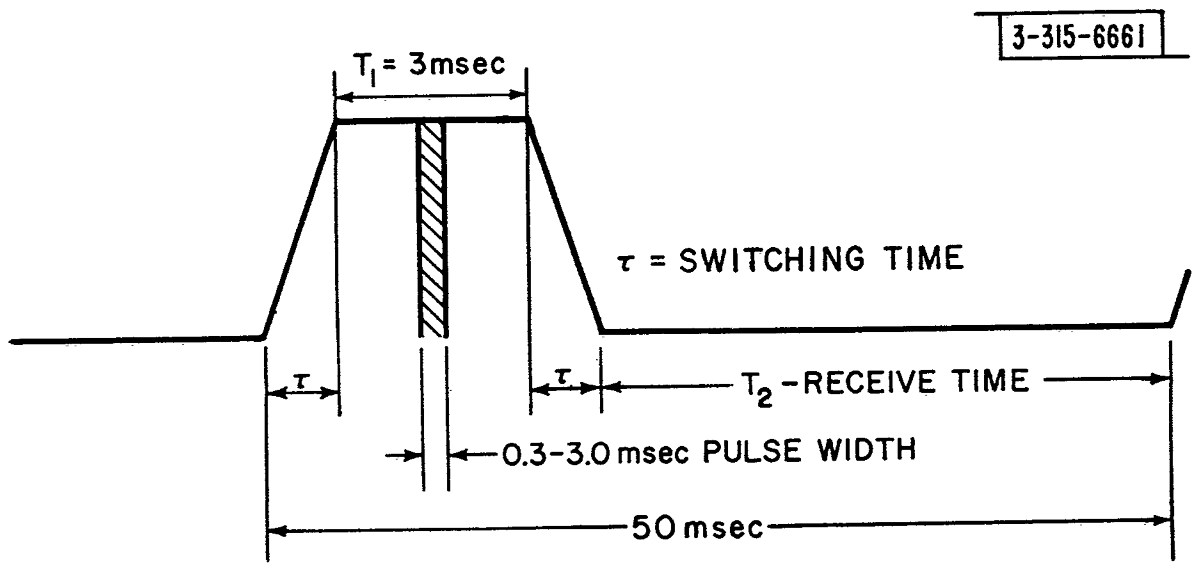

3-315-6661
T_1 = 3msec
τ = SWITCHING TIME
τ
τ
T_2 -RECEIVE TIME
0.3-3.0 msec PULSE WIDTH
50 msec

Figure 2

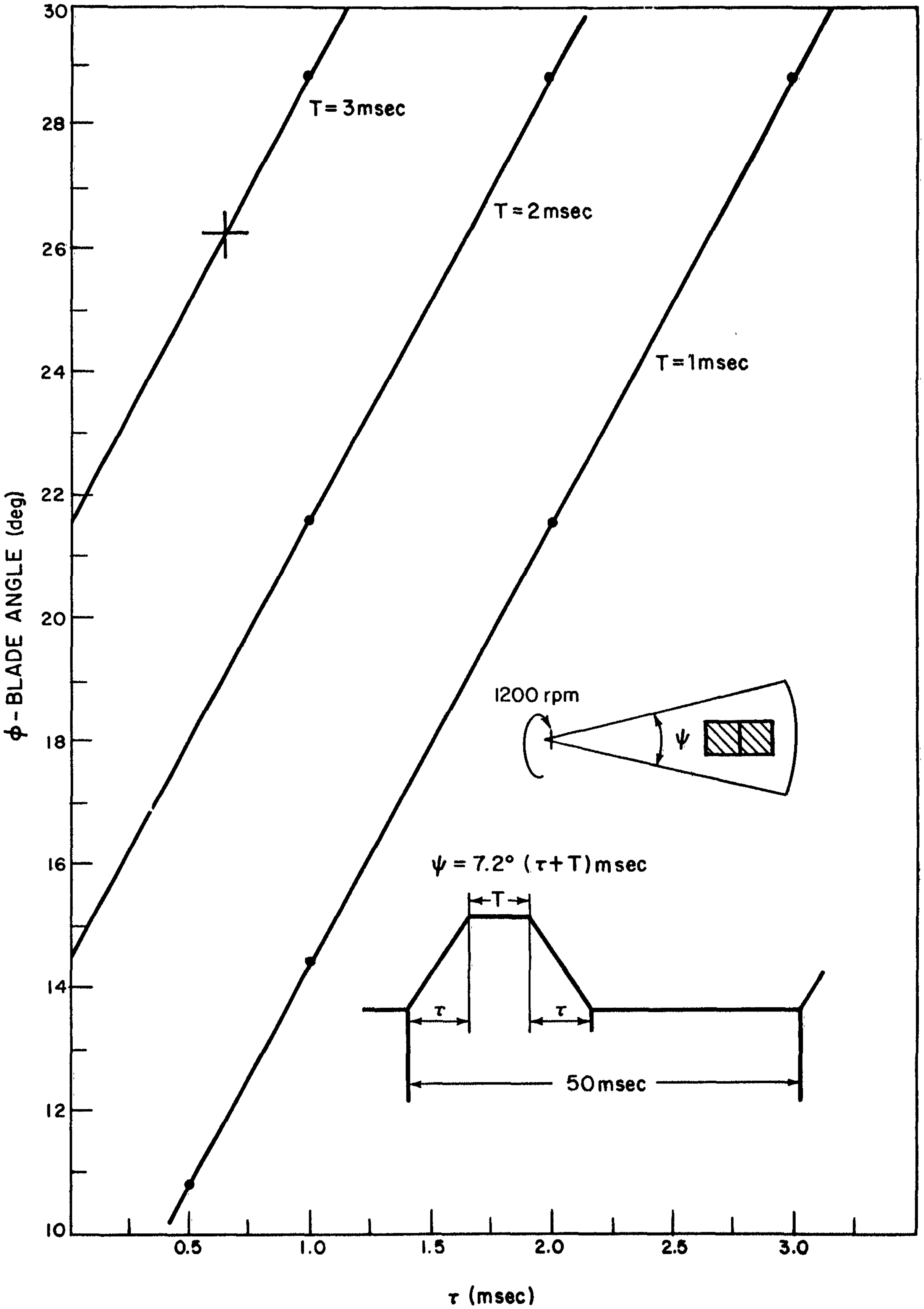
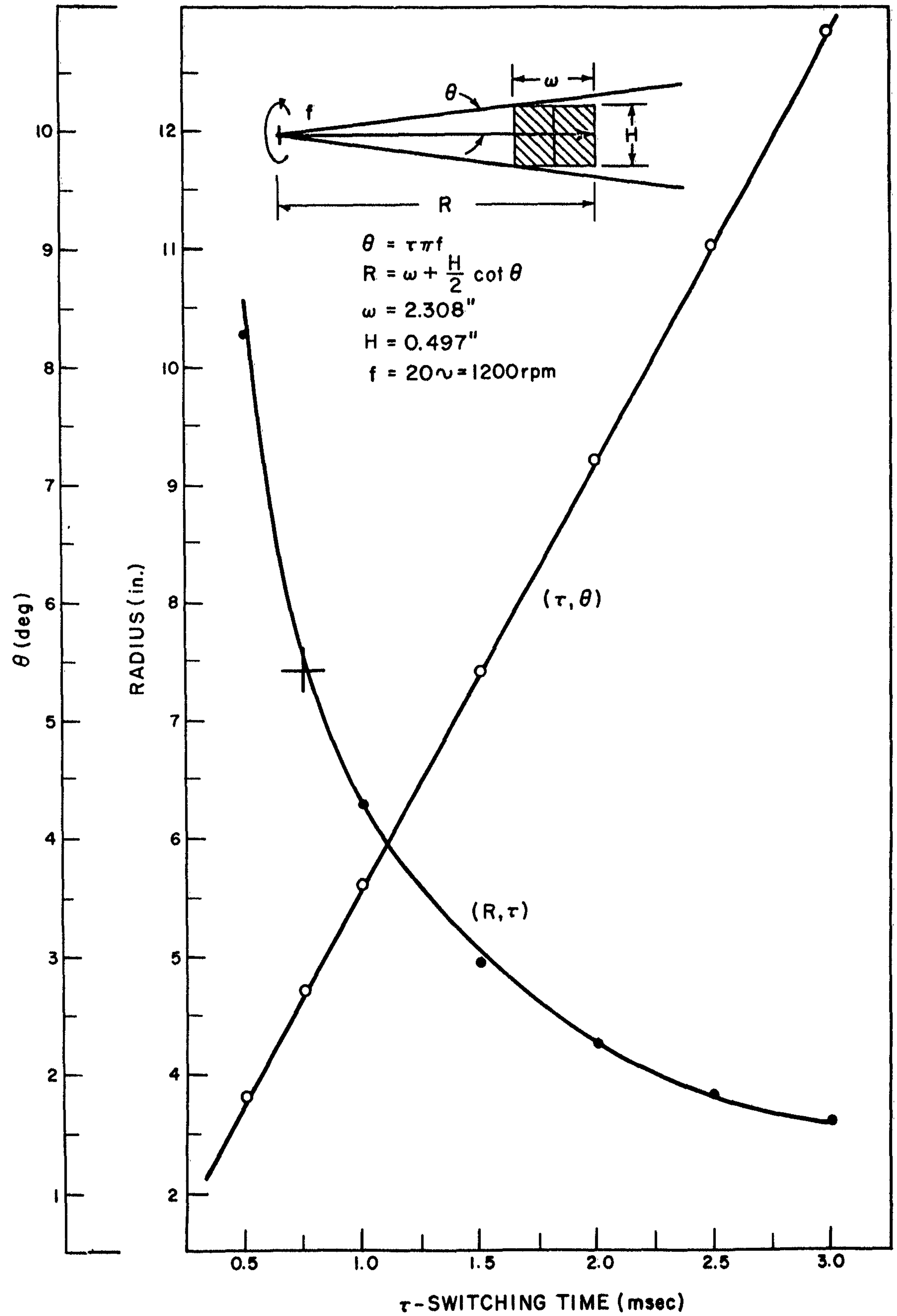

30
28
26
24
22
20
18
16
14
12
10
φ - BLADE ANGLE (deg)
T = 3 msec
T = 2 msec
T = 1 msec
1200 rpm
ψ
ψ = 7.2° (τ + T) msec
T
τ
τ
50 msec
0.5
1.0
1.5
2.0
2.5
3.0
τ (msec)

Figure 4



f
θ
ω
H
R
θ = τπf
R = ω + H/2 cot θ
ω = 2.308"
H = 0.497"
f = 20∿ = 1200rpm
(τ, θ)
(R, τ)
θ (deg)
RADIUS (in.)
τ - SWITCHING TIME (msec)
0.5
1.0
1.5
2.0
2.5
3.0

Figure 5

Figure 5

Figure 7

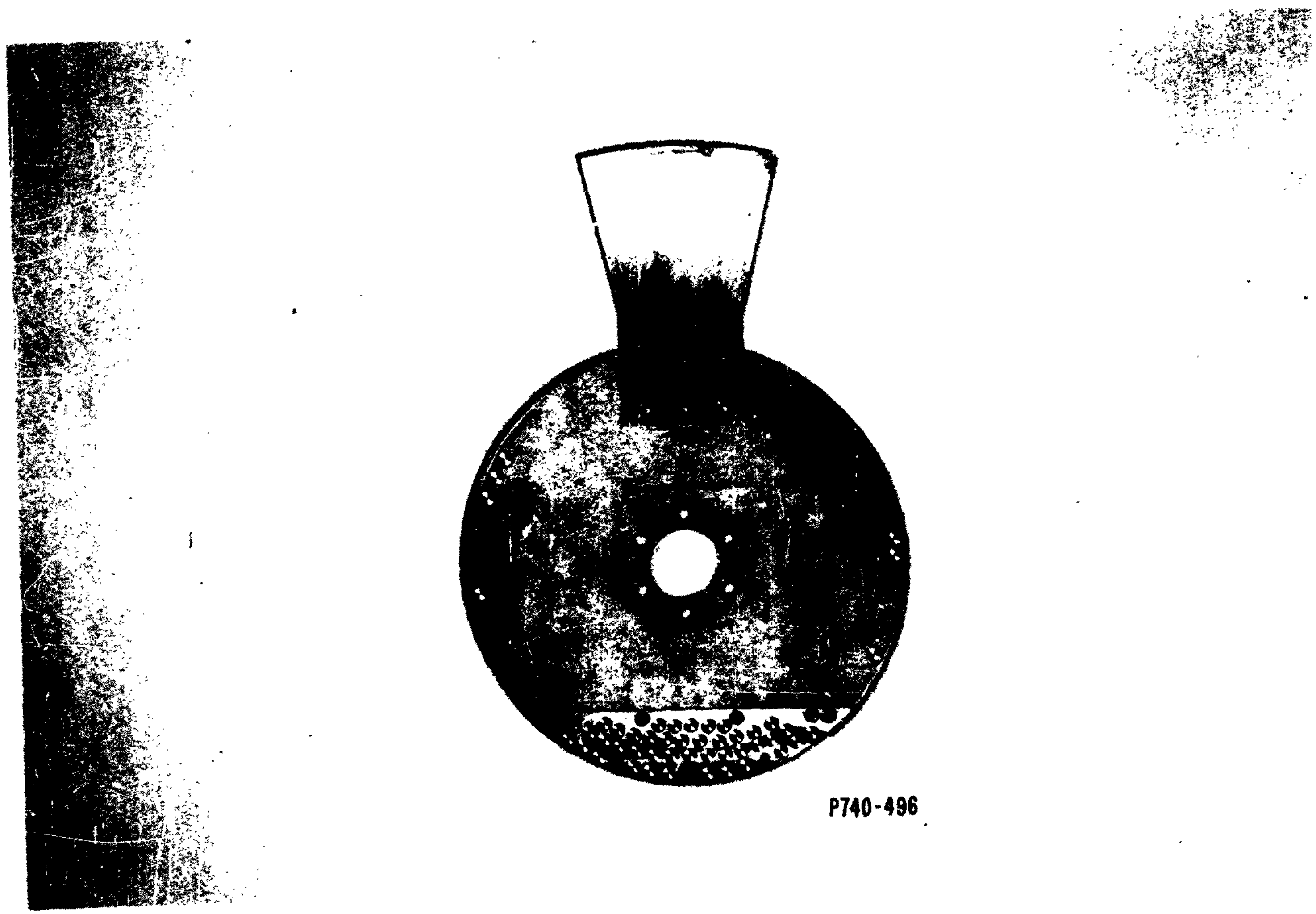


Figure 8

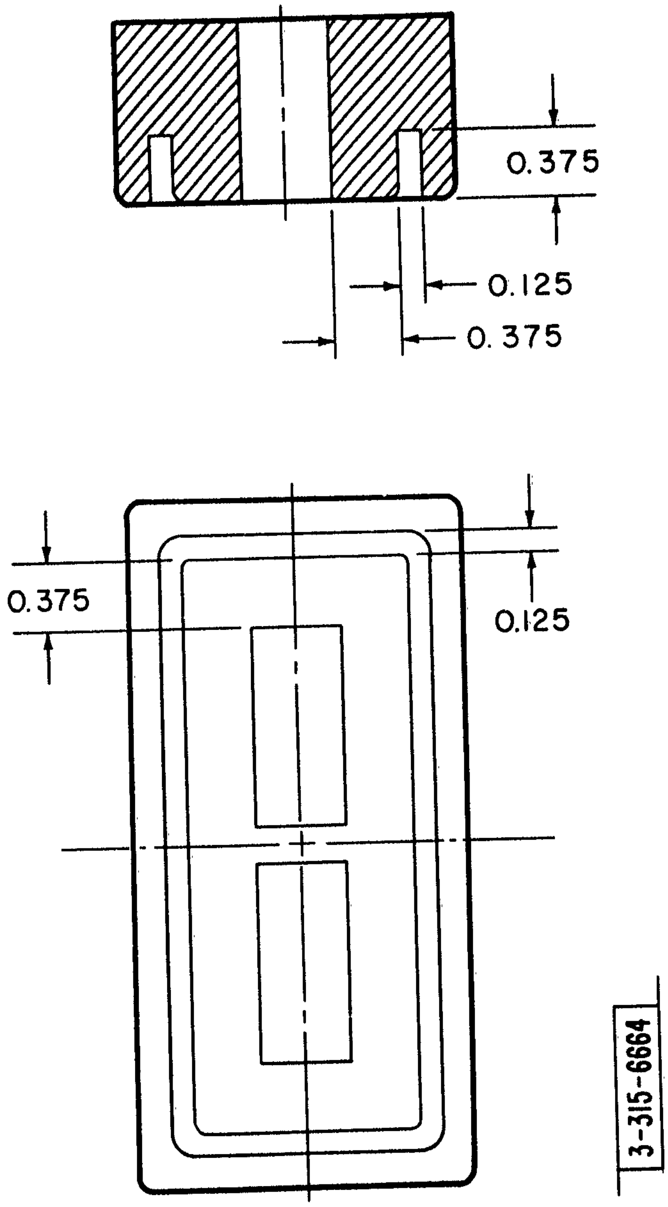


Figure 9

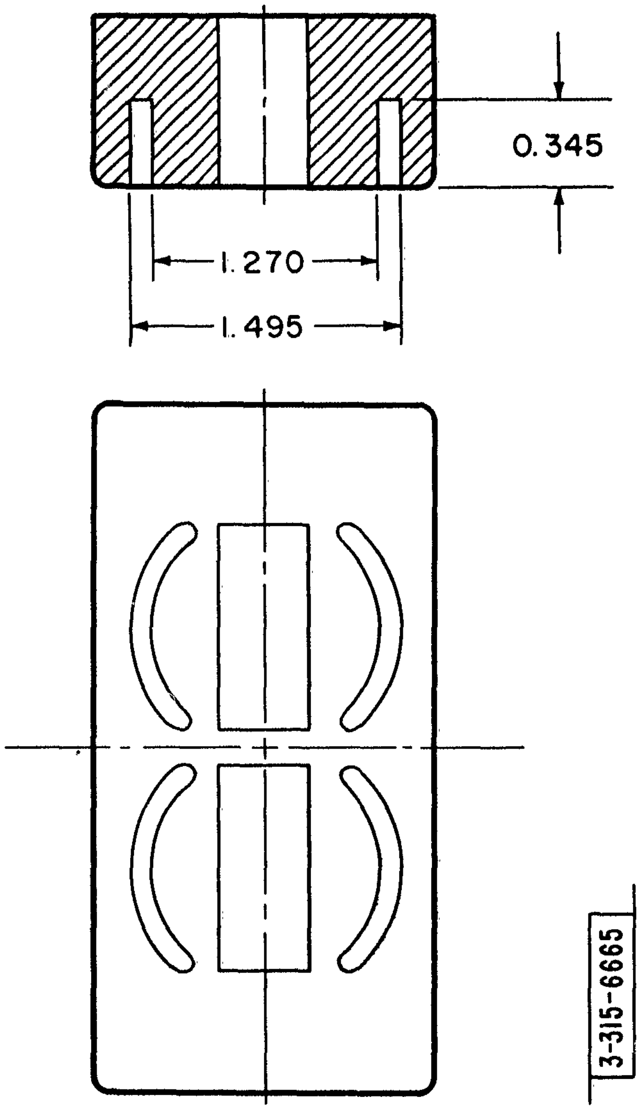


Figure 10

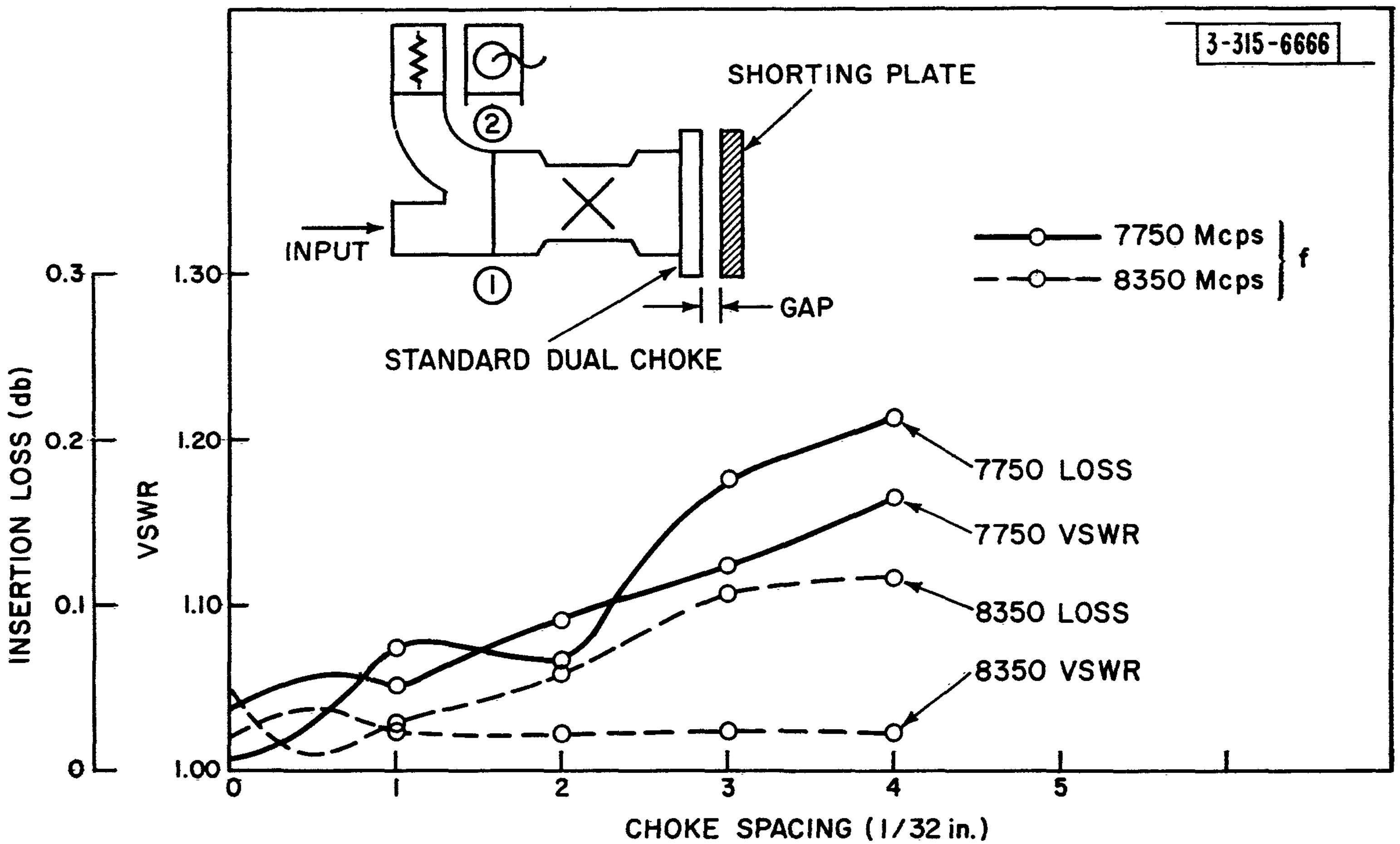

3-315-6666
SHORTING PLATE
INPUT
STANDARD DUAL CHOKE
GAP
7750 Mcps
8350 Mcps
f
INSERTION LOSS (db)
VSWR
0.3
0.2
0.1
0
1.30
1.20
1.10
1.00
7750 LOSS
7750 VSWR
8350 LOSS
8350 VSWR
0
1
2
3
4
5
CHOKE SPACING (1/32 in.)

Figure 11

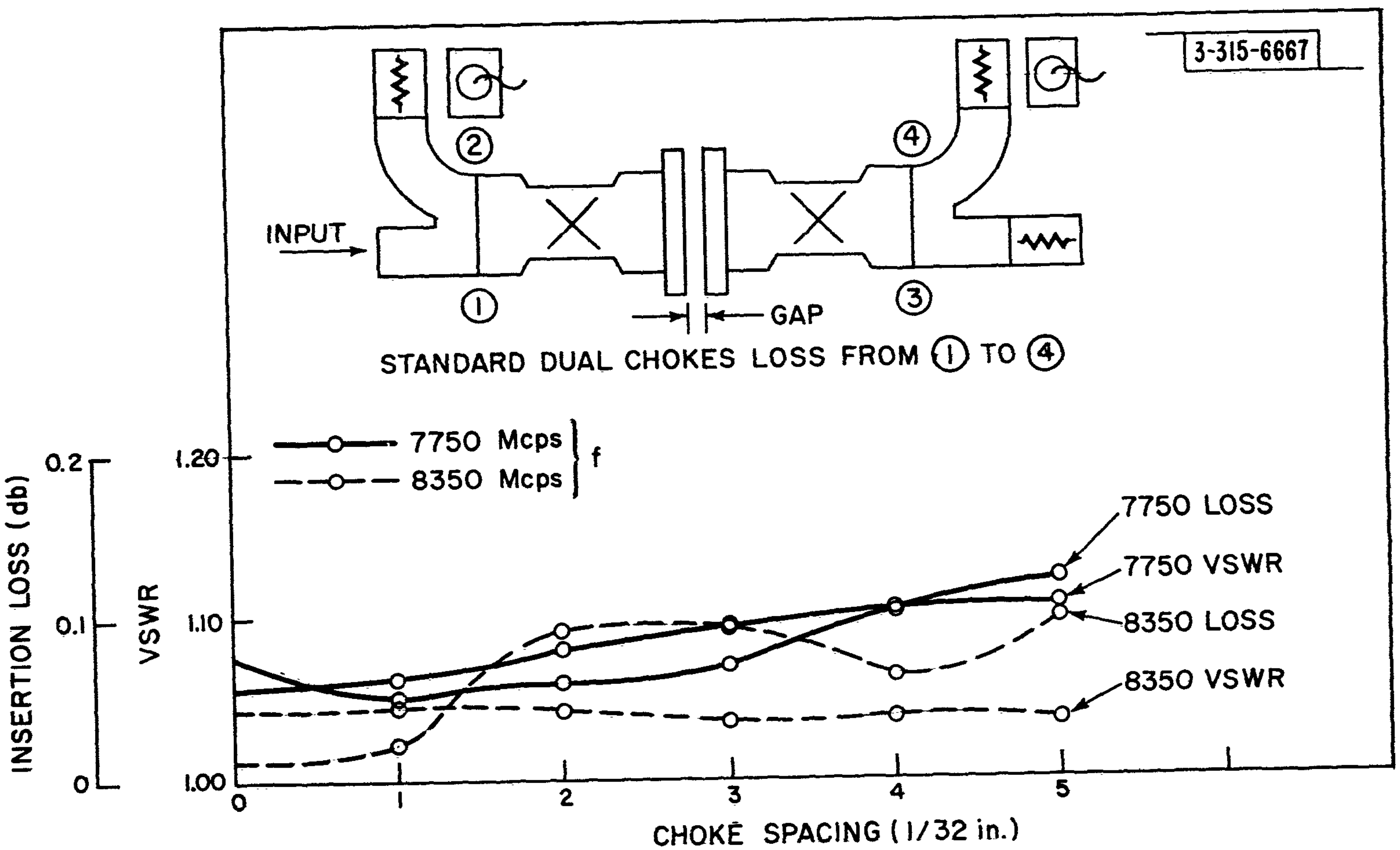

3-315-6667
INPUT
GAP
STANDARD DUAL CHOKES LOSS FROM 1 TO 4
7750 Mcps
8350 Mcps
f
7750 LOSS
7750 VSWR
8350 LOSS
8350 VSWR
INSERTION LOSS (db)
VSWR
0.2
0.1
0
1.20
1.10
1.00
0
1
2
3
4
5
CHOKE SPACING (1/32 in.)

Figure 12

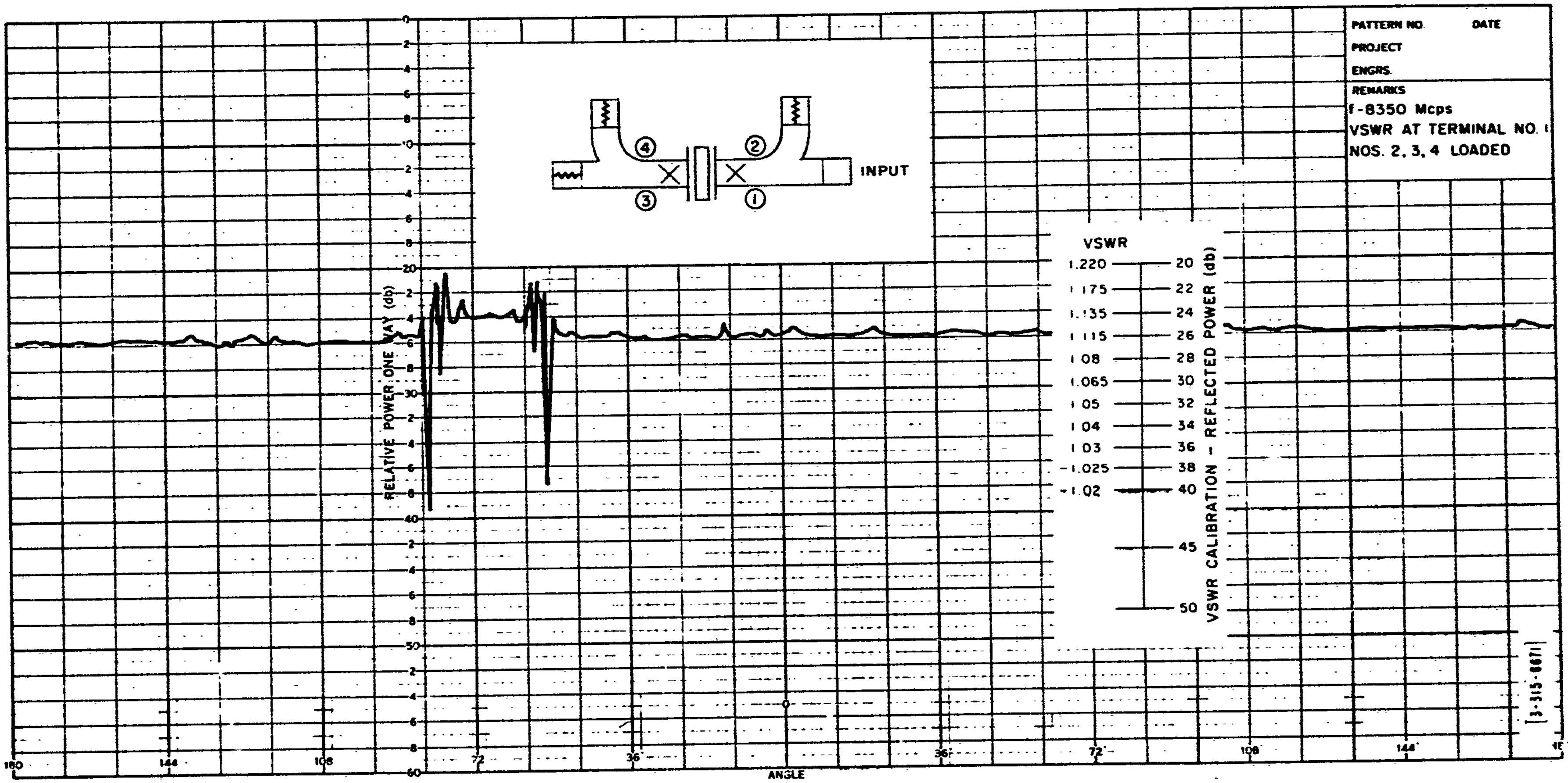
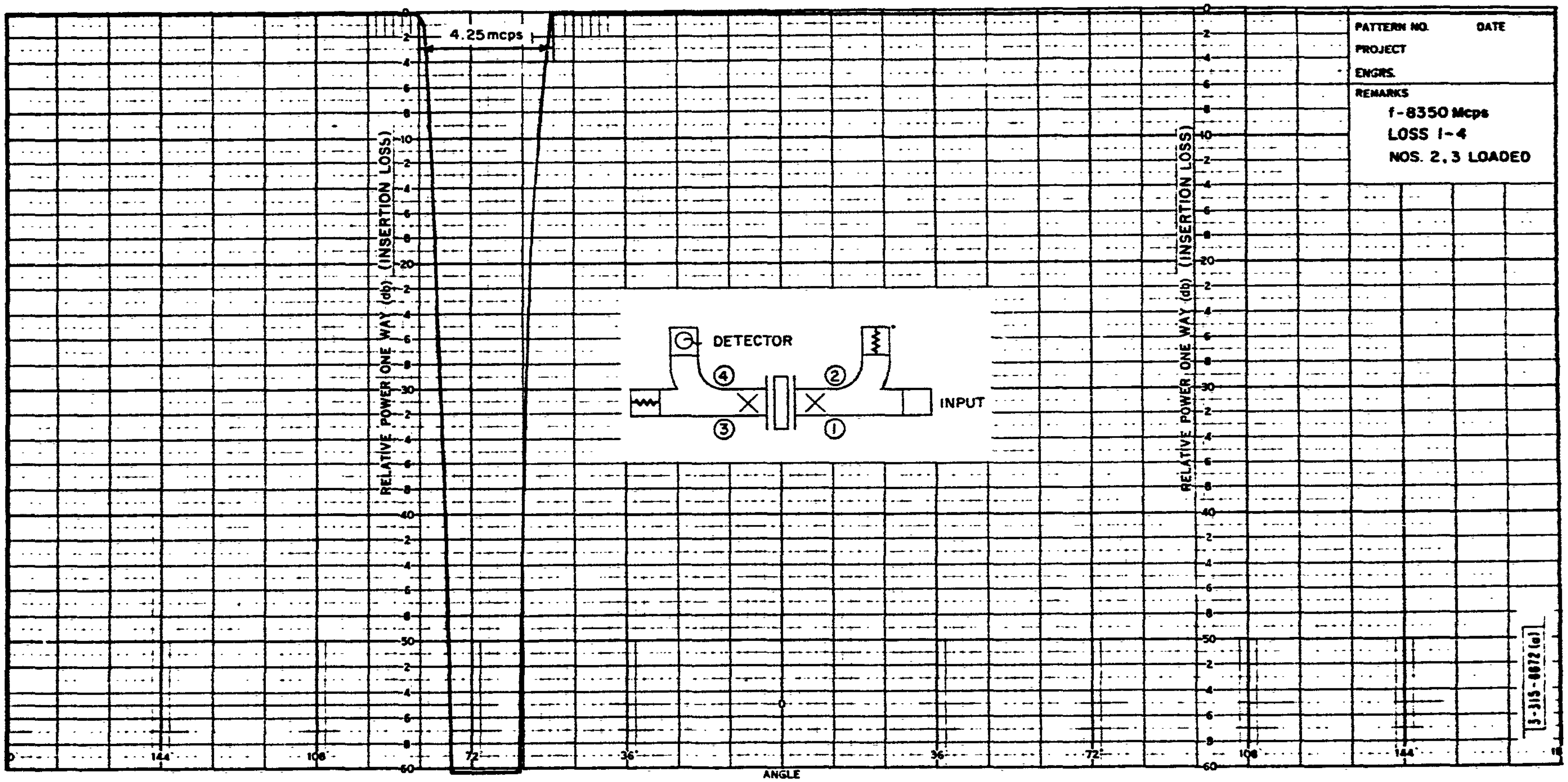

PATTERN NO.
DATE
PROJECT
ENGRS.
REMARKS
f-8350 Mcps
VSWR AT TERMINAL NO. 1
NOS. 2, 3, 4 LOADED
INPUT
VSWR
VSWR CALIBRATION - REFLECTED POWER (db)
RELATIVE POWER ONE WAY (db)
ANGLE
3-315-8871

Figure 13



4.25 mcps
RELATIVE POWER ONE WAY (db) (INSERTION LOSS)
DETECTOR
INPUT
ANGLE
PATTERN NO.
DATE
PROJECT
ENGRS.
REMARKS
f-8350 Mcps
LOSS 1-4
NOS. 2,3 LOADED
3-315-8872(a)

Figure 14(a)

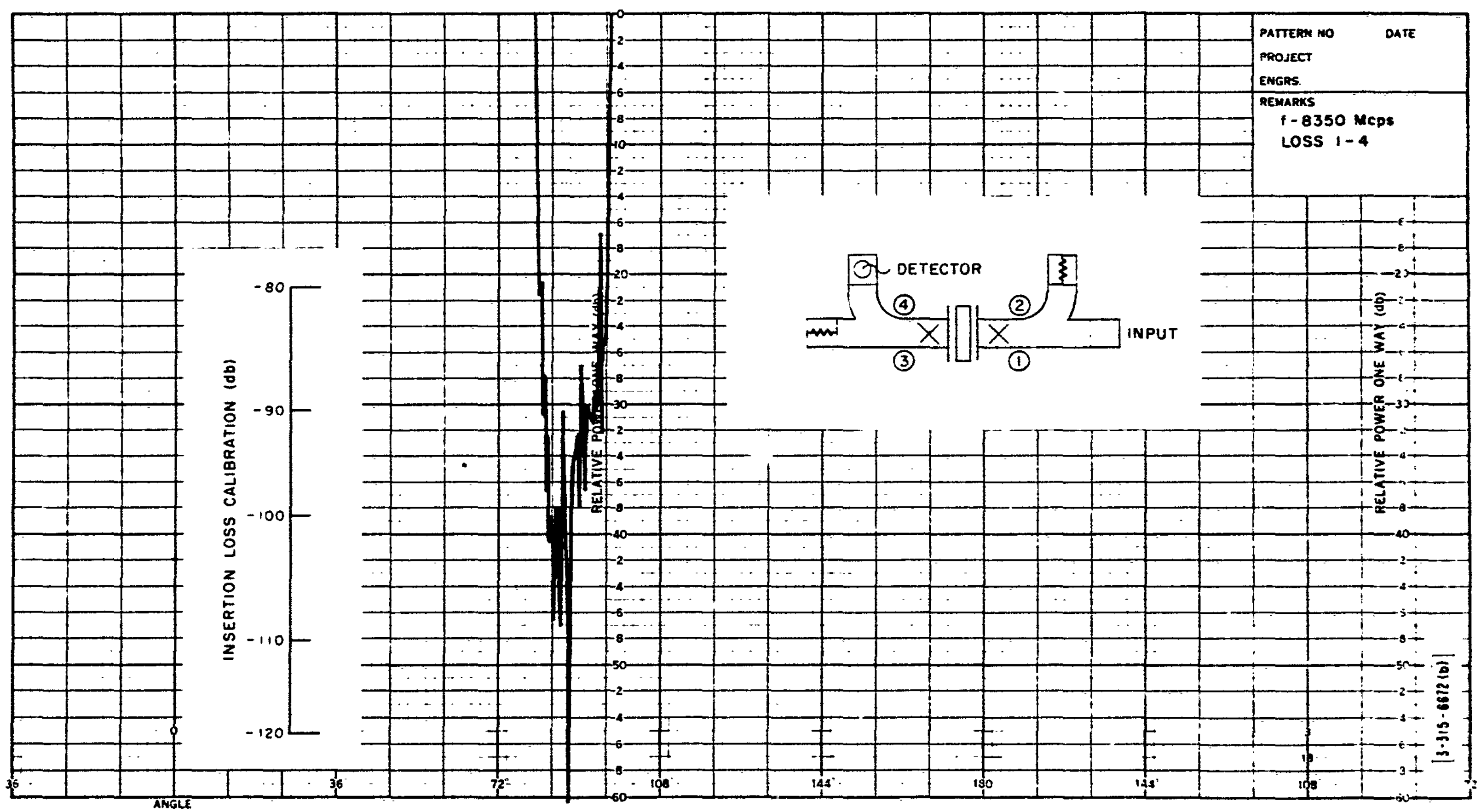
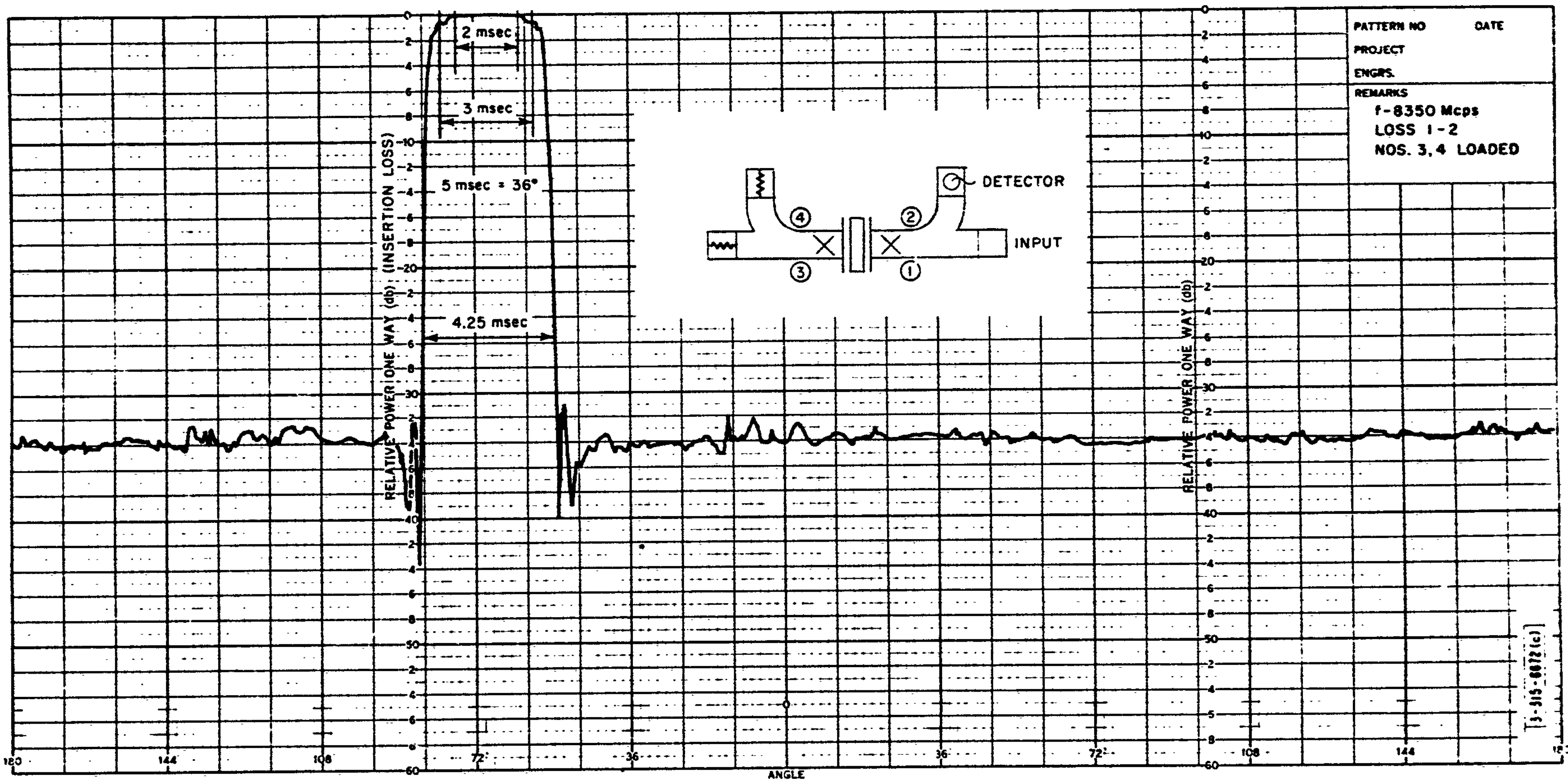

PATTERN NO
DATE
PROJECT
ENGRS.
REMARKS
f - 8350 Mcps
LOSS 1 - 4
DETECTOR
INPUT
INSERTION LOSS CALIBRATION (db)
- 80
- 90
- 100
- 110
- 120
RELATIVE POWER ONE WAY (db)
ANGLE
3-315-6672 (b)

Figure 14(b)



PATTERN NO
DATE
PROJECT
ENGRS.
REMARKS
f-8350 Mcps
LOSS 1-2
NOS. 3, 4 LOADED
DETECTOR
INPUT
2 msec
3 msec
5 msec = 36°
4.25 msec
RELATIVE POWER ONE WAY (db) (INSERTION LOSS)
RELATIVE POWER ONE WAY (db)
ANGLE
3-315-6672(c)

Figure 14(c)

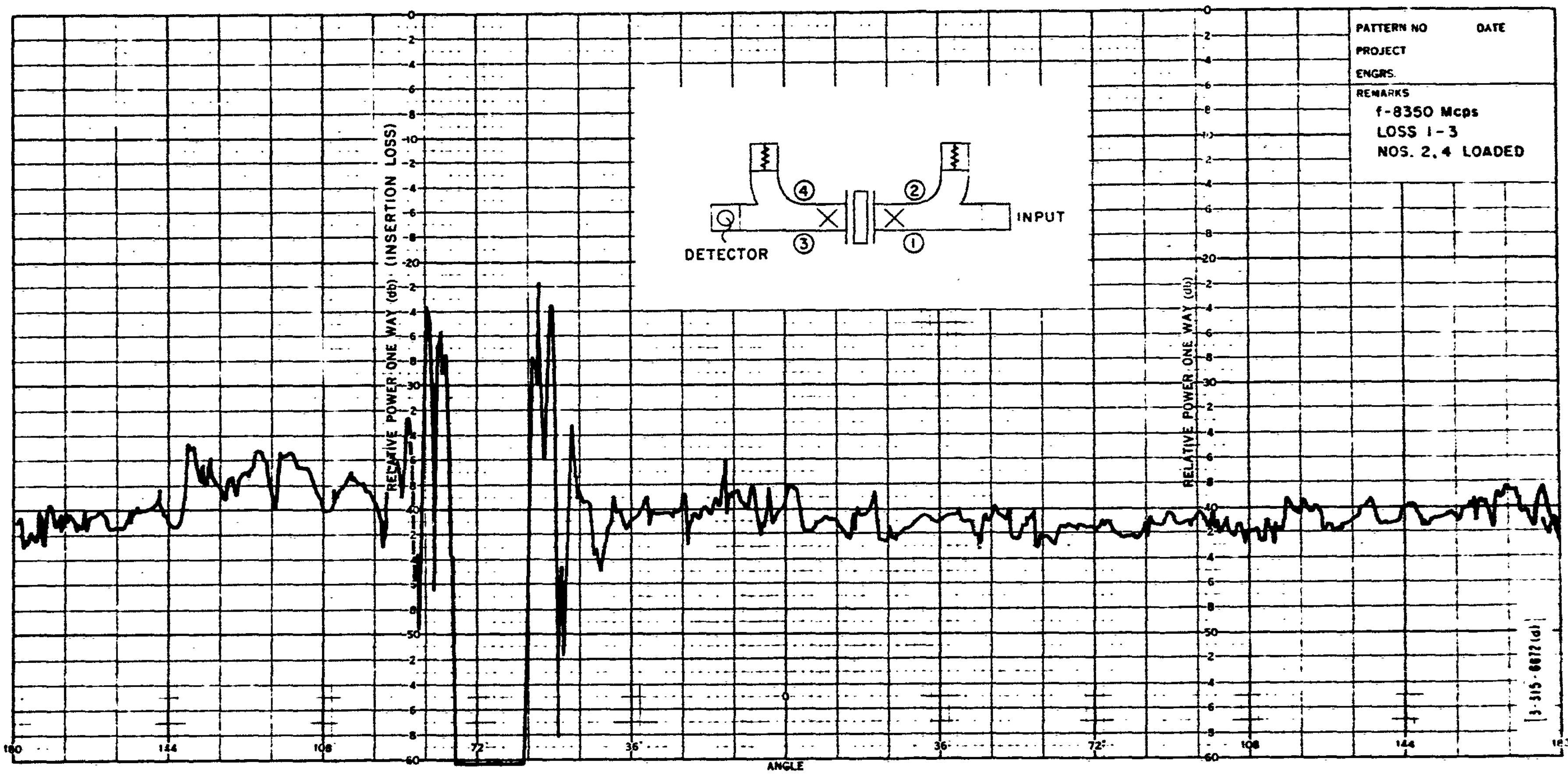

PATTERN NO
DATE
PROJECT
ENGRS.
REMARKS
f-8350 Mcps
LOSS 1-3
NOS. 2, 4 LOADED
DETECTOR
INPUT
RELATIVE POWER ONE WAY (db) (INSERTION LOSS)
RELATIVE POWER ONE WAY (db)
ANGLE
3-315-6672(d)

Figure 14(d)

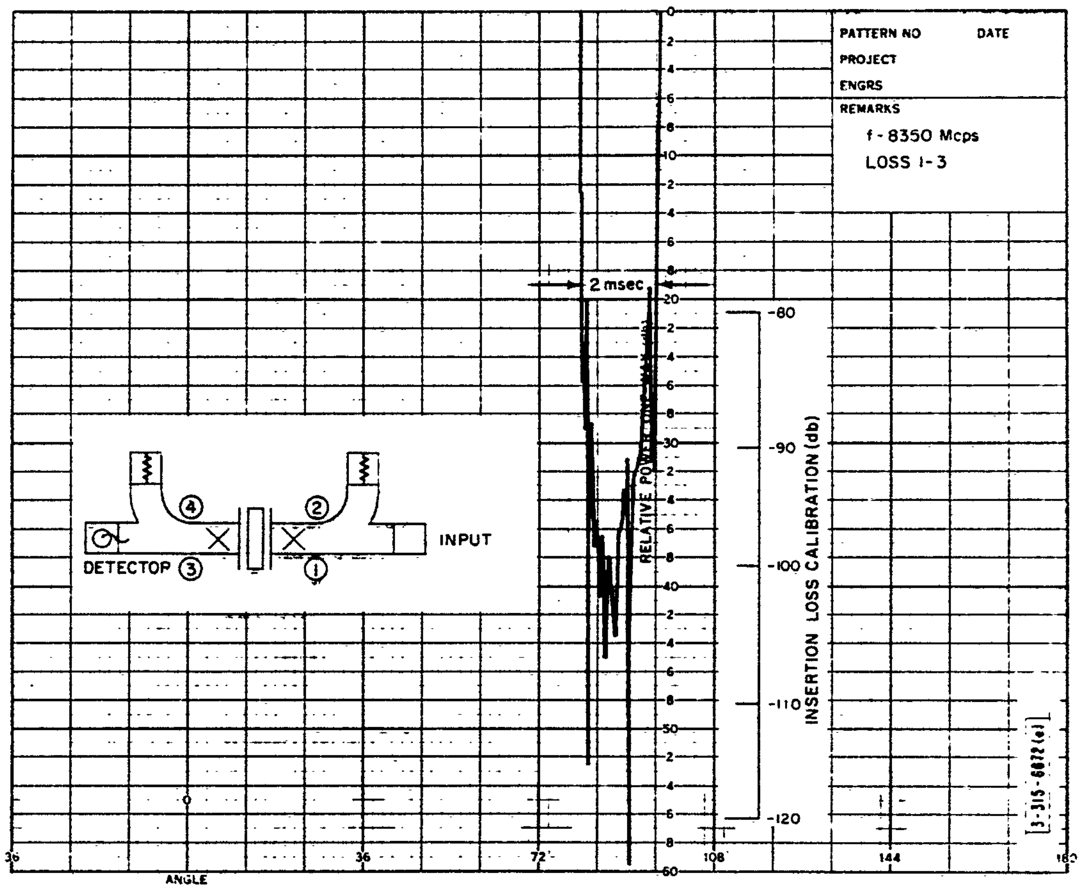

PATTERN NO
DATE
PROJECT
ENGRS
REMARKS
f - 8350 Mcps
LOSS 1-3
2 msec
RELATIVE POWER
INSERTION LOSS CALIBRATION (db)
-80
-90
-100
-110
-120
DETECTOR
INPUT
ANGLE
3-315-6872(e)

Figure 14(e)

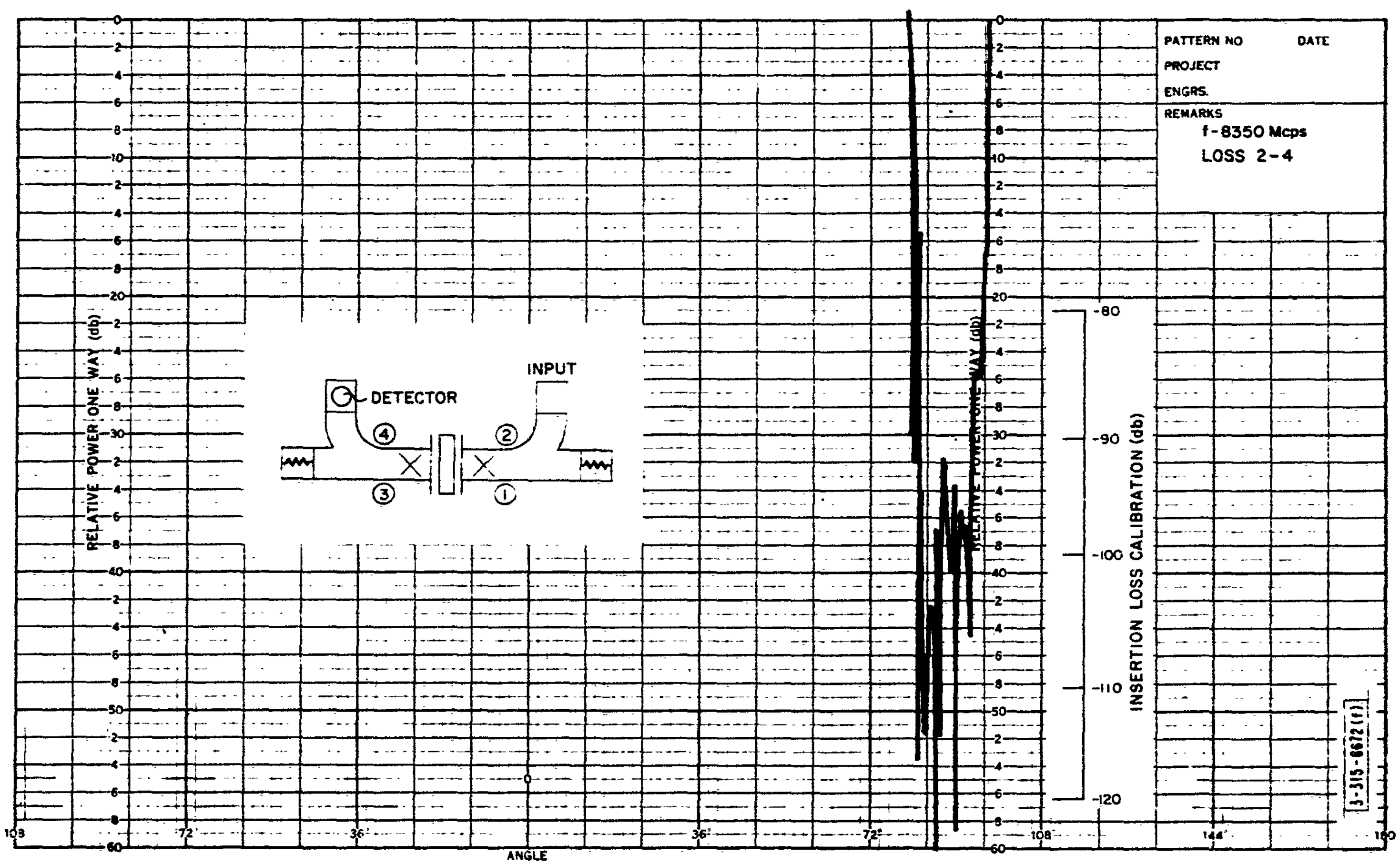

PATTERN NO
DATE
PROJECT
ENGRS.
REMARKS
f-8350 Mcps
LOSS 2-4
DETECTOR
INPUT
RELATIVE POWER ONE WAY (db)
INSERTION LOSS CALIBRATION (db)
-80
-90
-100
-110
-120
ANGLE
3-315-6672(f)

Figure 14(f)

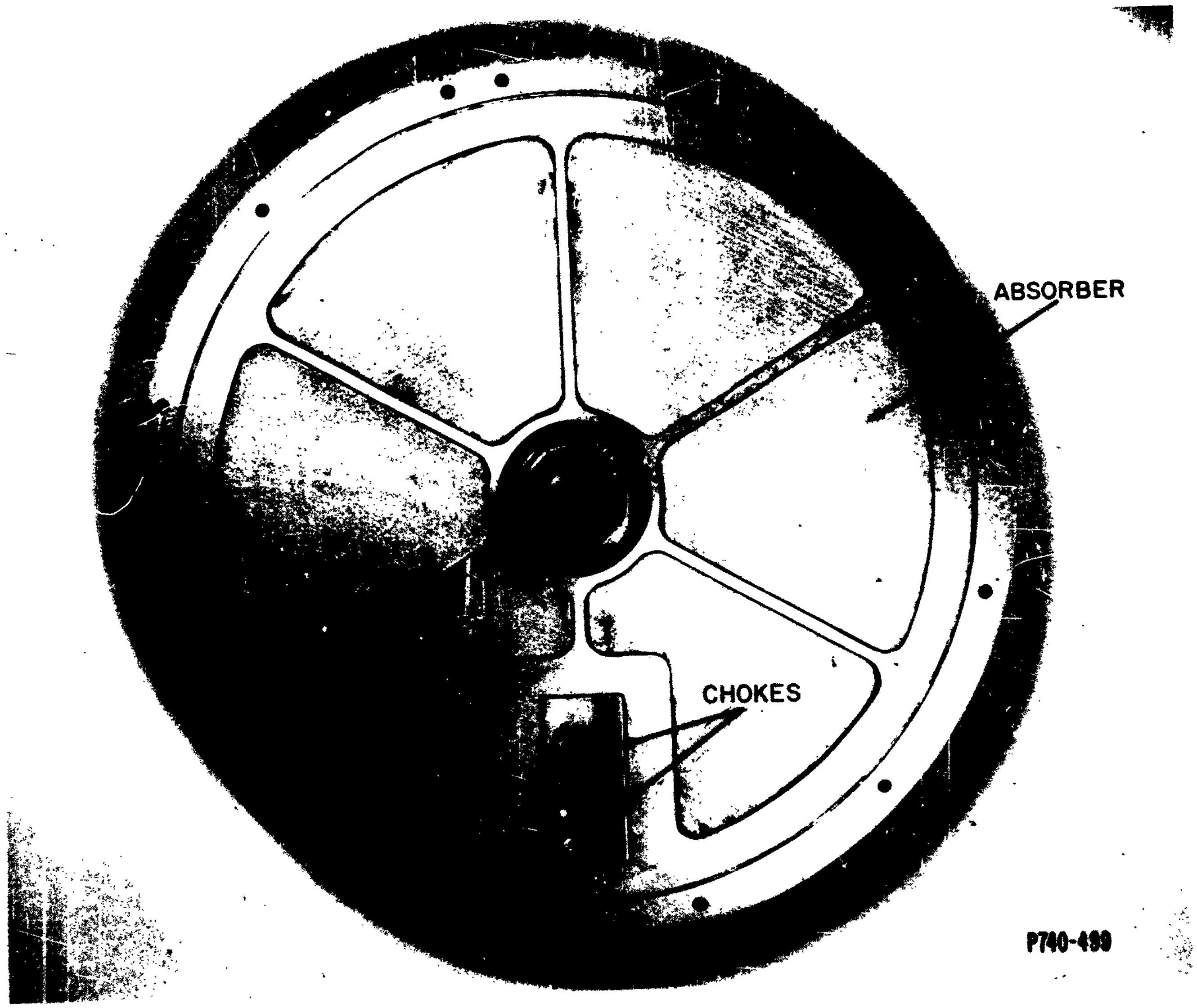


Figure 15

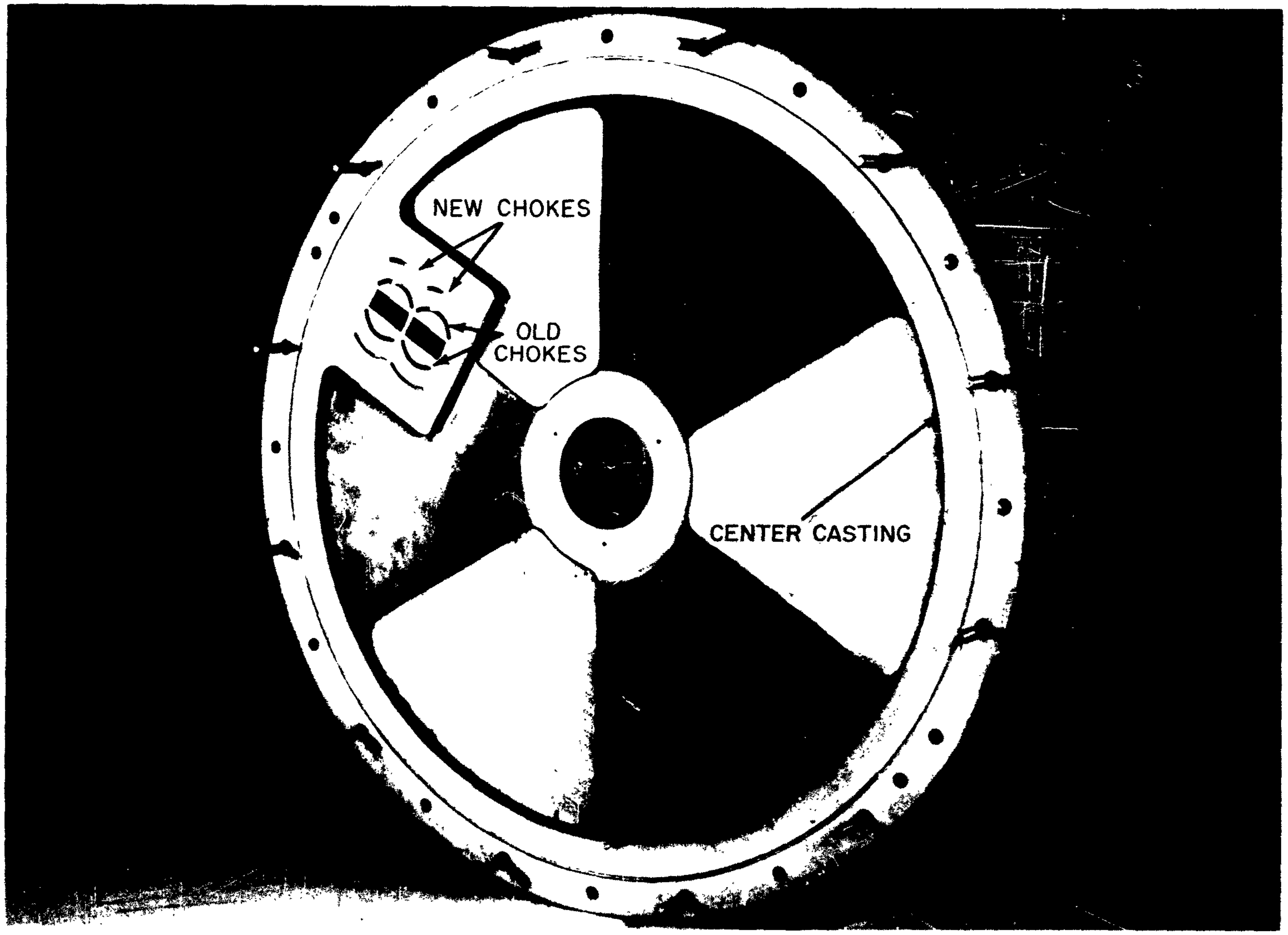


Figure 16

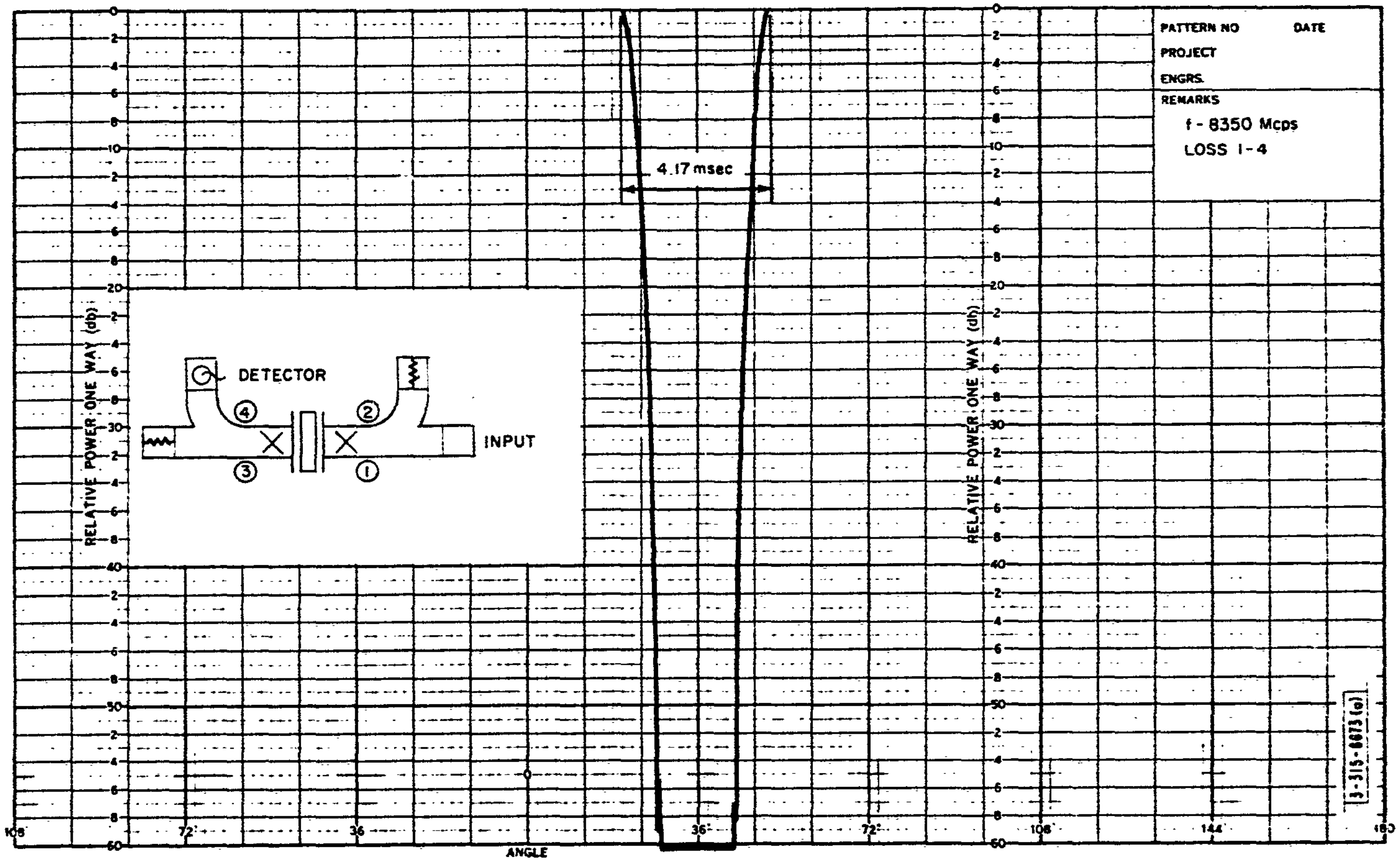

PATTERN NO
DATE
PROJECT
ENGRS.
REMARKS
f - 8350 Mcps
LOSS 1-4
4.17 msec
DETECTOR
INPUT
RELATIVE POWER ONE WAY (db)
ANGLE
3-315-6673(a)

Figure 17(a)

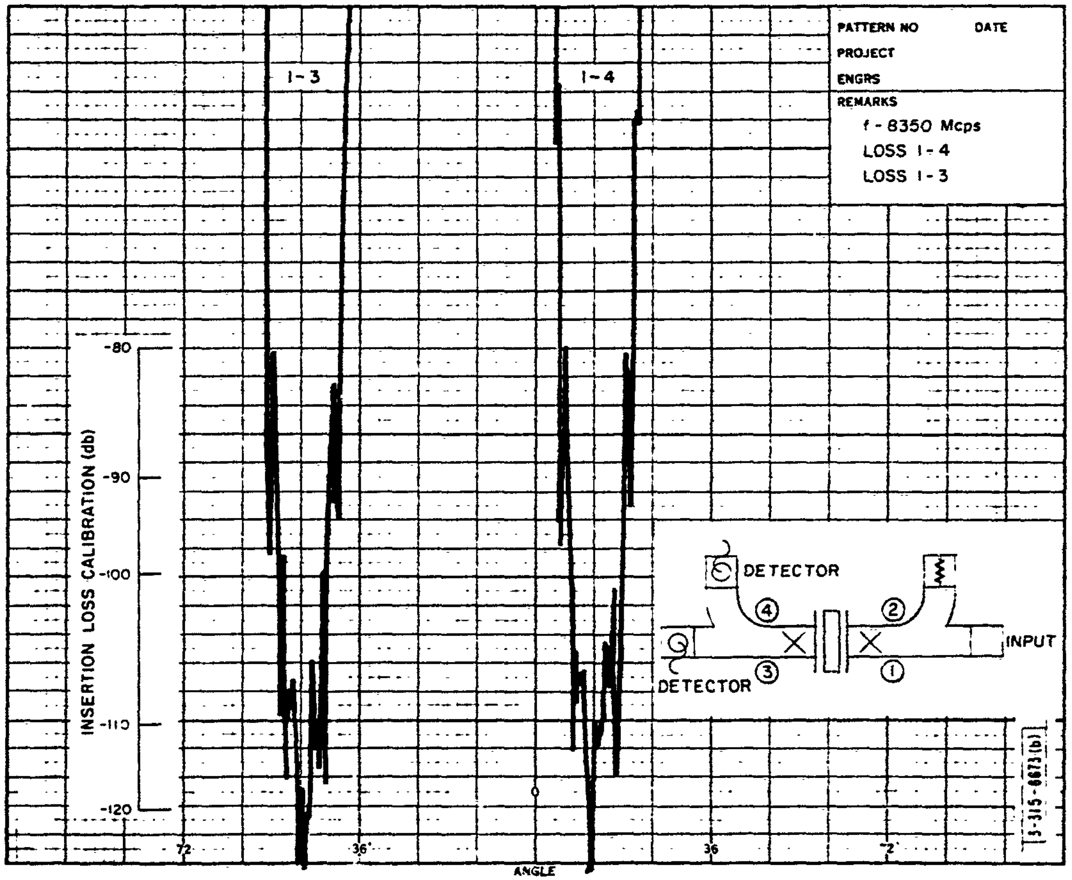

PATTERN NO
DATE
PROJECT
ENGRS
REMARKS
f - 8350 Mcps
LOSS 1 - 4
LOSS 1 - 3
1-3
1-4
INSERTION LOSS CALIBRATION (db)
-80
-90
-100
-110
-120
72
36
0
36
72
ANGLE
DETECTOR
DETECTOR
INPUT
4
3
2
1
S-315-6673(b)

Figure 17(b)

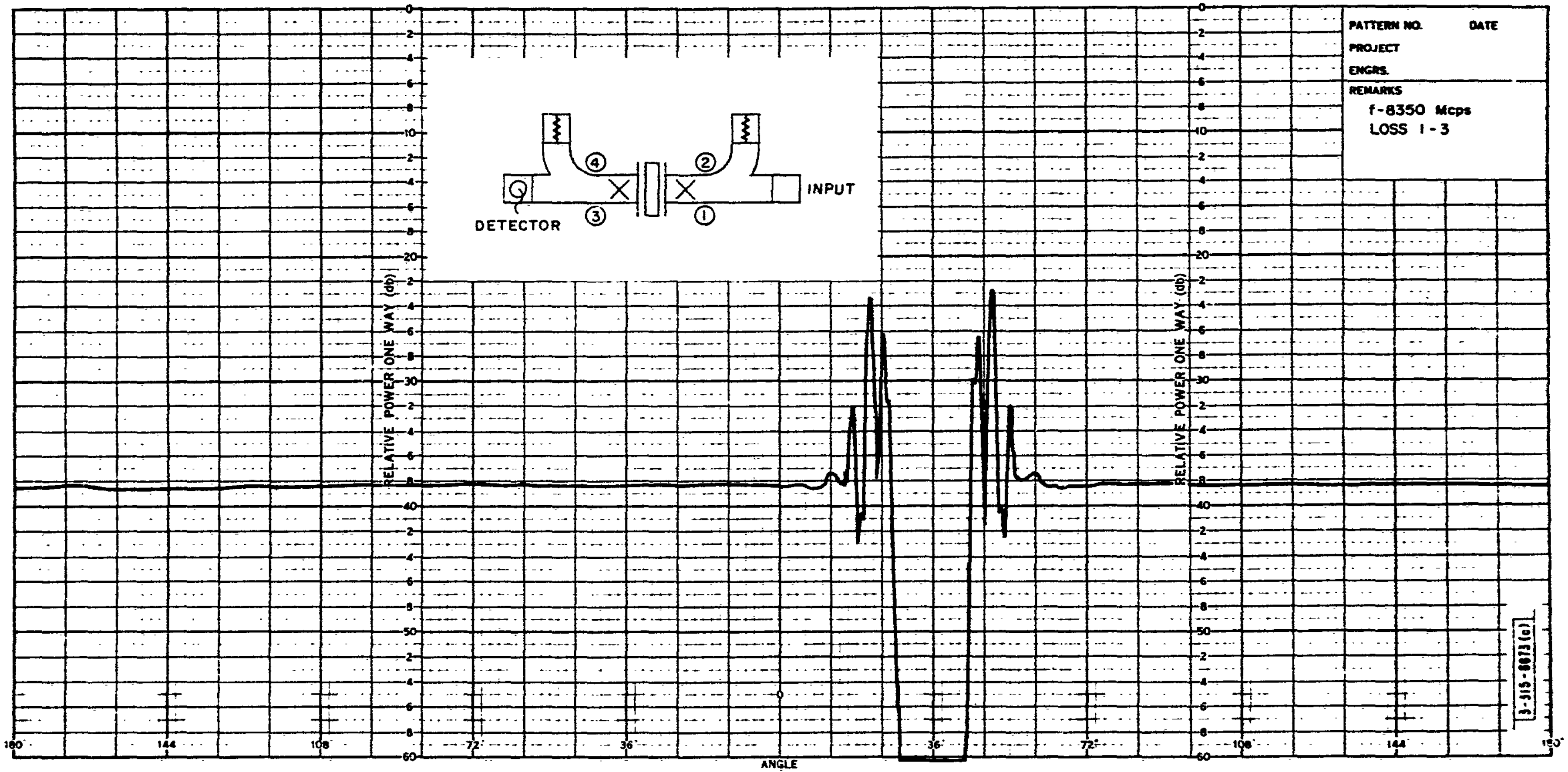
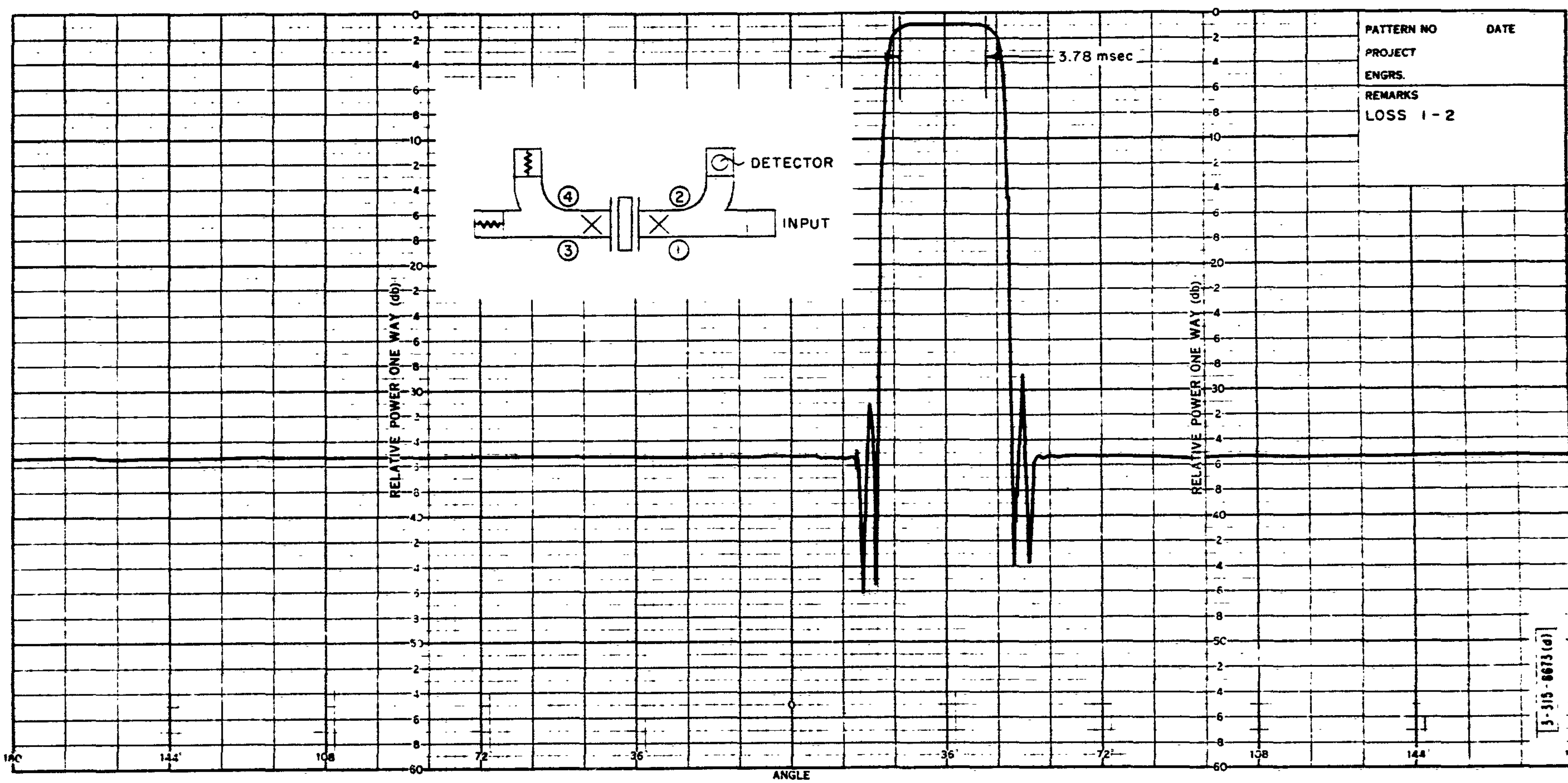

PATTERN NO.
DATE
PROJECT
ENGRS.
REMARKS
f-8350 Mcps
LOSS 1-3
INPUT
DETECTOR
RELATIVE POWER ONE WAY (db)
ANGLE
3-315-8873(c)

Figure 17(c)



PATTERN NO
DATE
PROJECT
ENGRS.
REMARKS
LOSS 1 - 2
3.78 msec
DETECTOR
INPUT
RELATIVE POWER ONE WAY (db)
ANGLE
S-315-8673(d)

Figure 17(d)

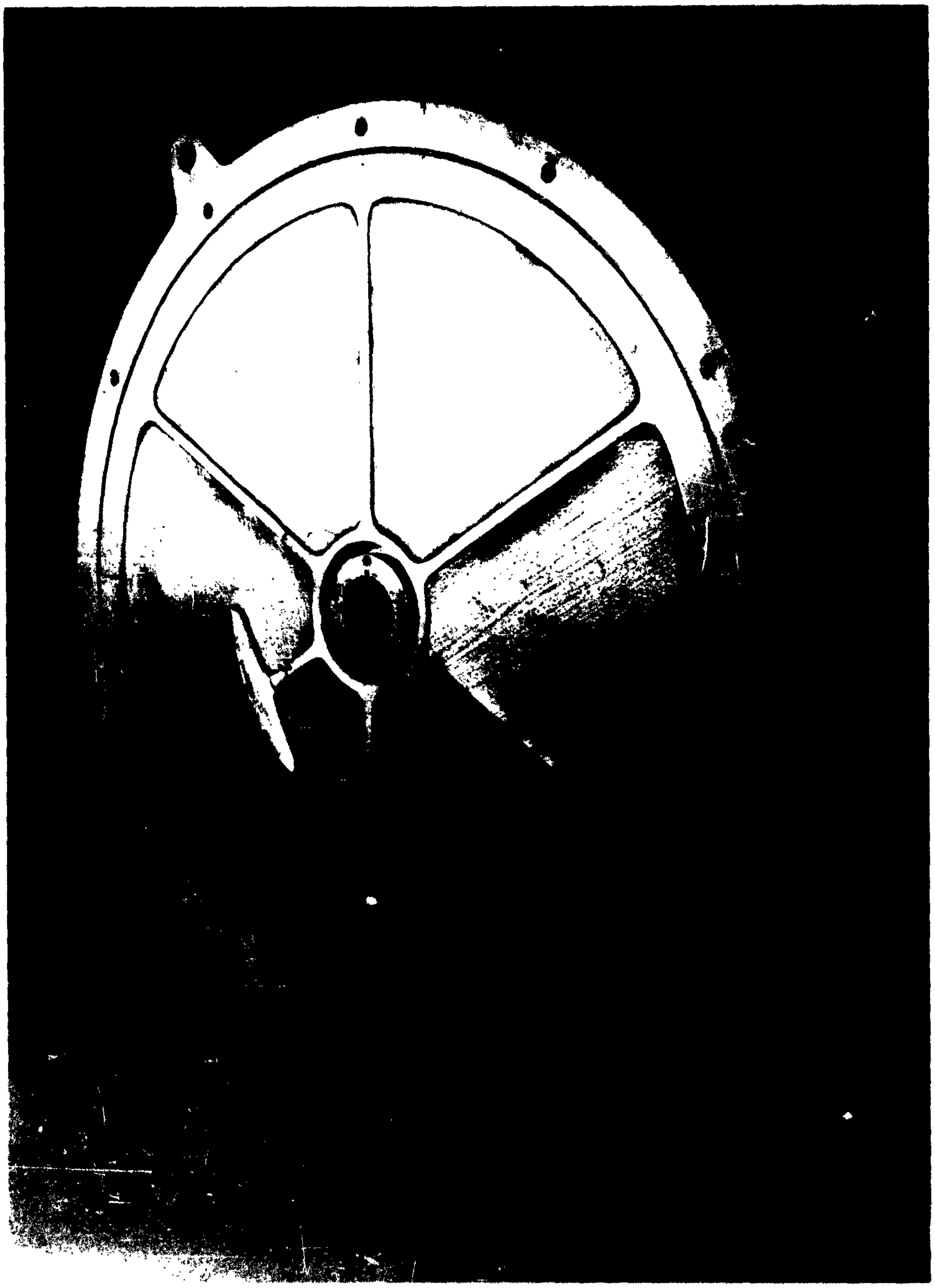


Figure 18

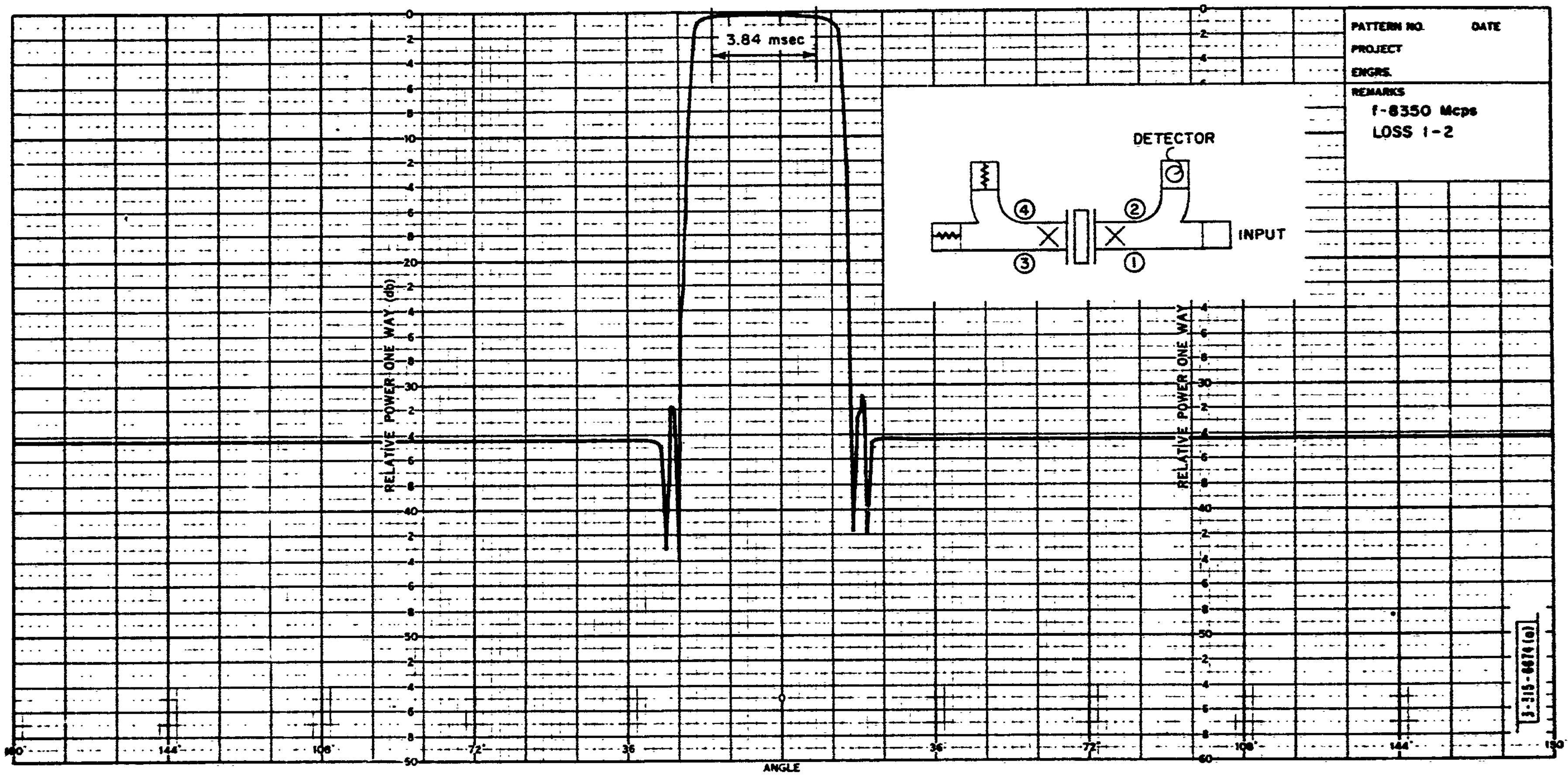

3.84 msec
DETECTOR
INPUT
PATTERN NO.
DATE
PROJECT
ENGRS.
REMARKS
f-8350 Mcps
LOSS 1-2
RELATIVE POWER ONE WAY (db)
ANGLE

Figure 19(a)

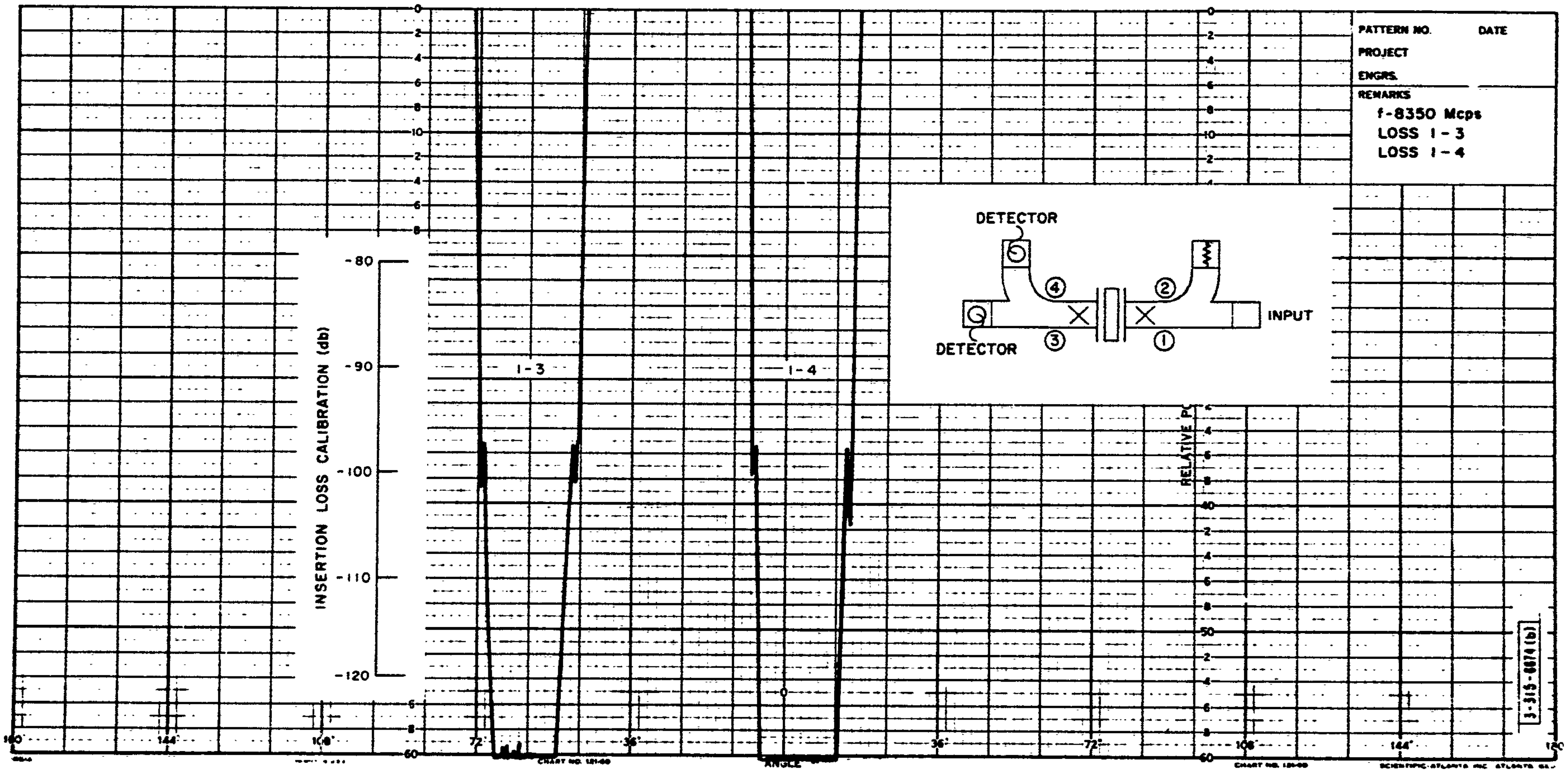

PATTERN NO.
DATE
PROJECT
ENGRS.
REMARKS
f-8350 Mcps
LOSS 1-3
LOSS 1-4
DETECTOR
DETECTOR
INPUT
INSERTION LOSS CALIBRATION (db)
-80
-90
-100
-110
-120
1-3
1-4
ANGLE
3-315-6674(b)

Figure 19(b)

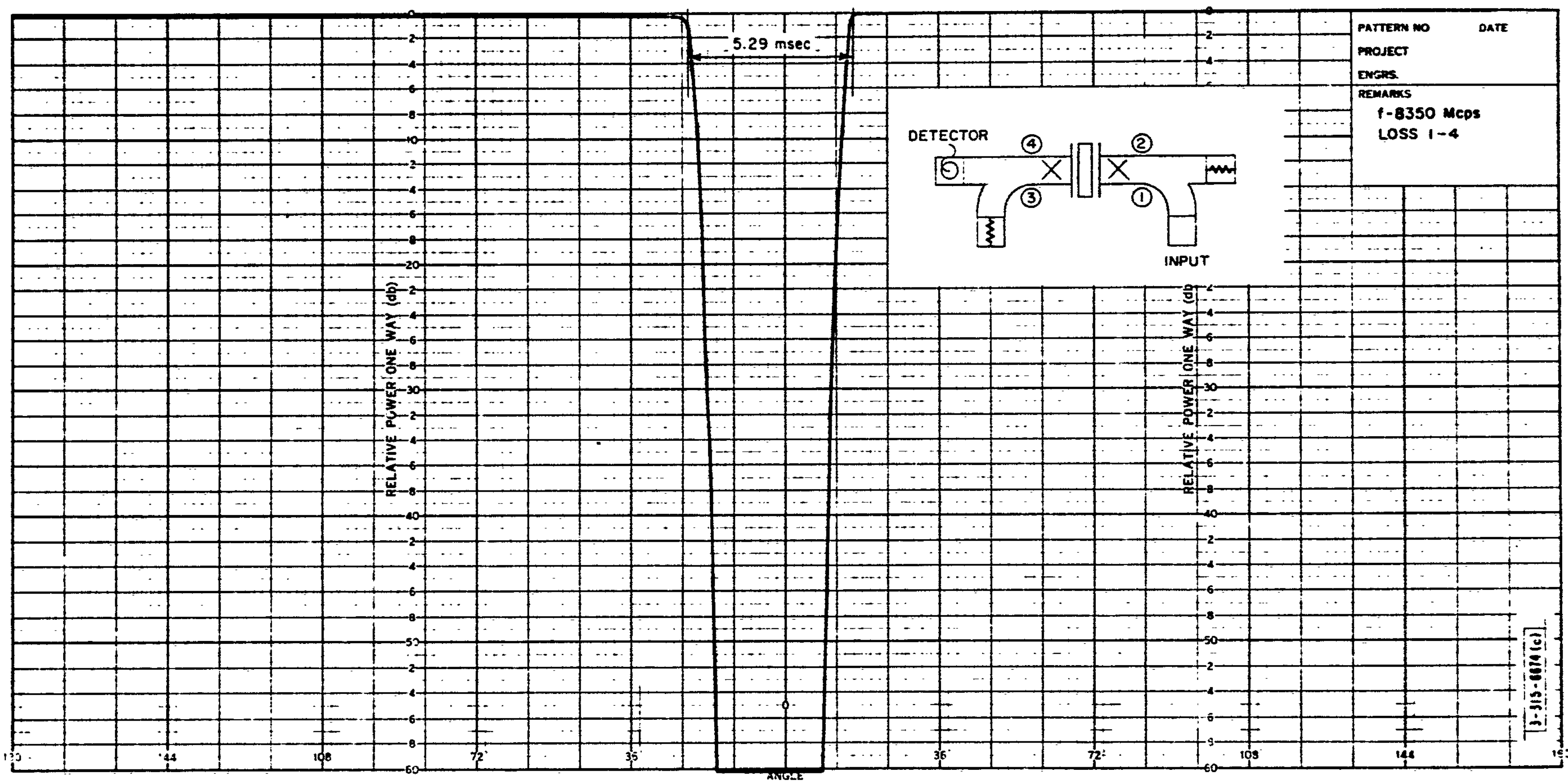

PATTERN NO
DATE
PROJECT
ENGRS.
REMARKS
f-8350 Mcps
LOSS 1-4
DETECTOR
INPUT
5.29 msec
RELATIVE POWER ONE WAY (db)
ANGLE
J-315-6074(c)

Figure 19(c)

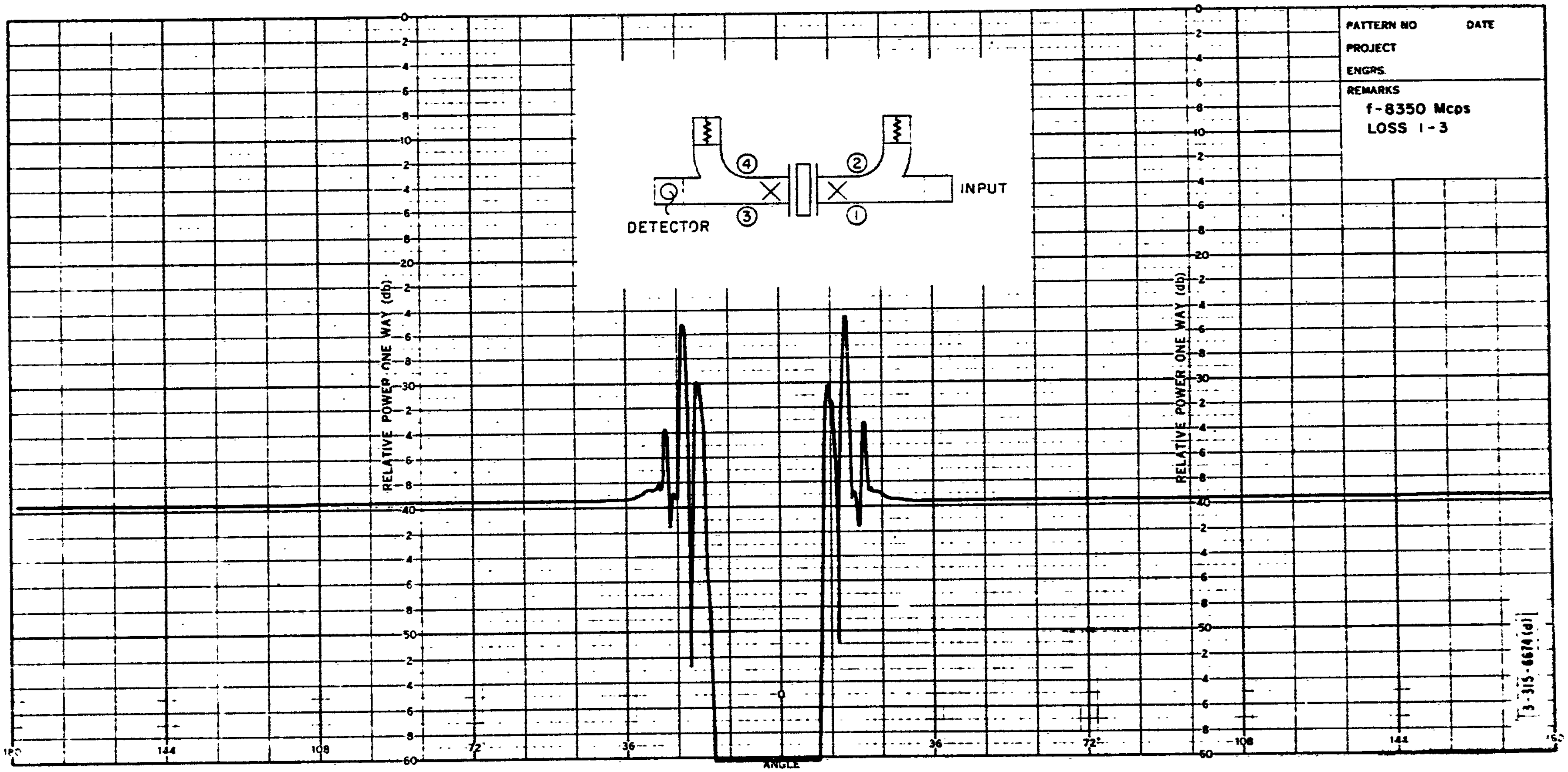

PATTERN NO
DATE
PROJECT
ENGRS.
REMARKS
f-8350 Mcps
LOSS 1-3
INPUT
DETECTOR
RELATIVE POWER ONE WAY (db)
ANGLE
3-315-6674(d)

Figure 19(d)

3-315-6668 (a-b)

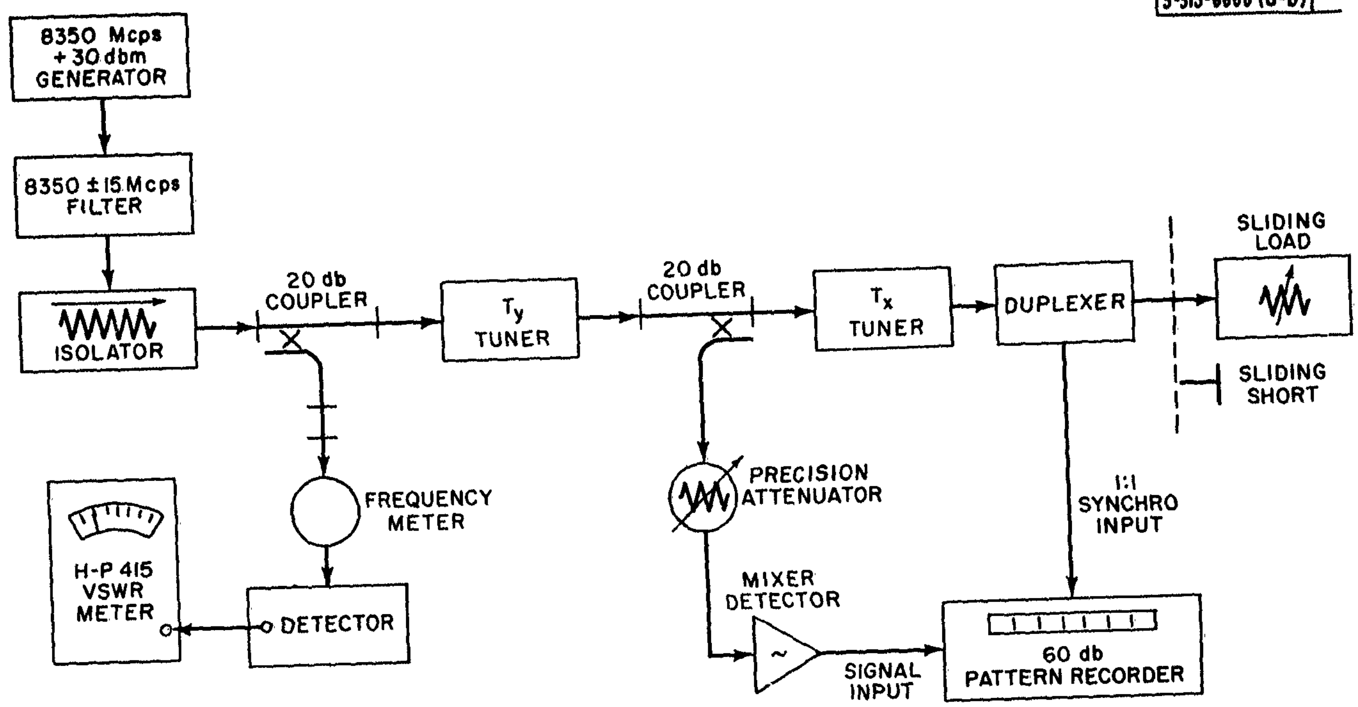


Figure 20 (a)

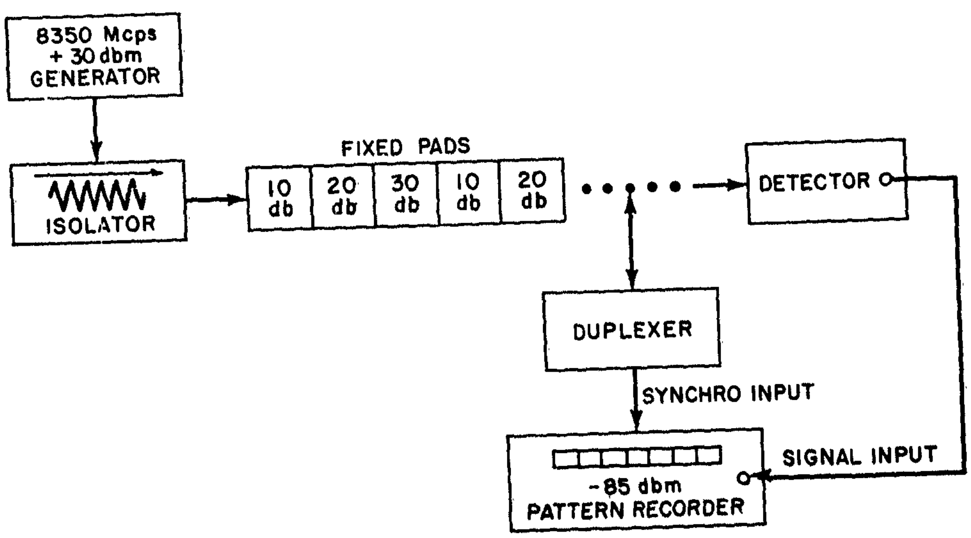
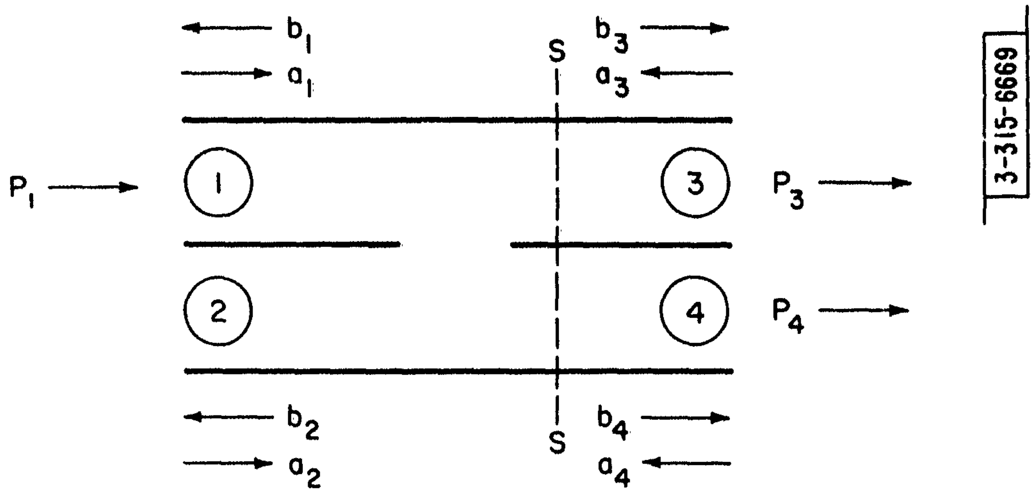
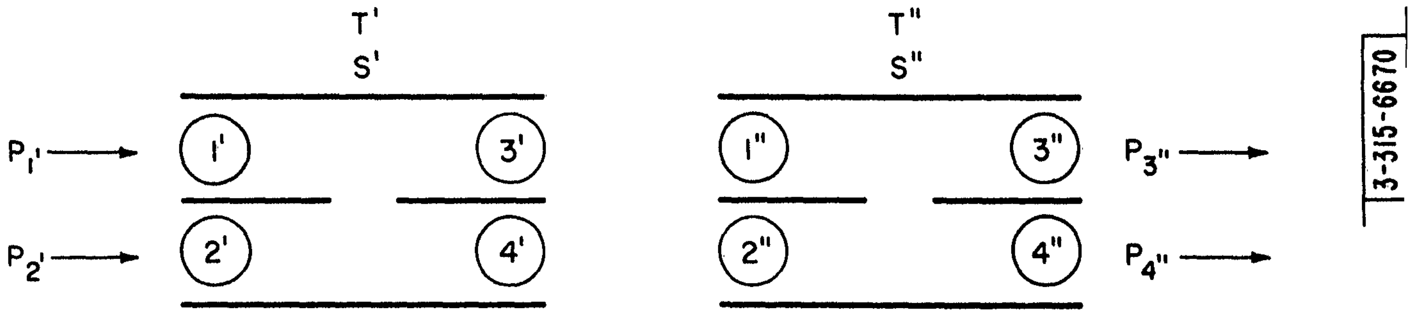


Figure 20 (b)



b1
a1
S
b3
a3
P1
1
3
P3
2
4
P4
b2
a2
S
b4
a4
3-315-6669

A-1



T'
S'
T"
S"
P1'
P2'
1'
2'
3'
4'
1"
2"
3"
4"
P3"
P4"
3-315-6670

A-2

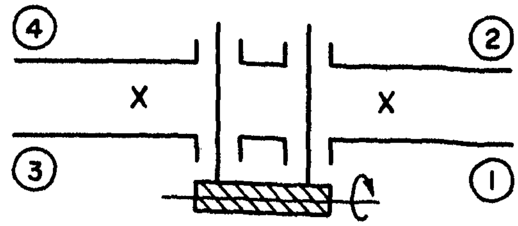
TABLE I

WEST FORD DUPLEXER REQUIREMENTS

Frequency	8350 Mcps ± 5 Mcps	
Power	10 kw Peak 1500 w Avg.	
VSWR	1.15 : 1 max	
Insertion Loss	Antenna to Maser Transmitter to Antenna	$\leqslant$ 0.2 db $\leqslant$ 0.2 db
Isolation	Transmitter to Maser	$\geqslant$ 120 db
Switching Time		$\leqslant$ 2 ms
Repetition Rate	20 cps	

TABLE 2

DUPLEXER INSERTION LOSS
(f – 8350 Mcps)



Ports	Blade Position	Loss (db)*
1 → 4	Out	0.115
1 → 2	In	0.081

* The loss reading is the average of at least five measurements.

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